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FRACTURE AND PULL-OUT BEHAVIOUR OF BASALT COMPOSITE FIBRES IN OSA-BASED CEMENTITIOUS MATRIX ASSESSED BY DCB TESTING APPROACH

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The fracture and pull-out behaviour of vertically aligned basalt composite fibres embedded in an oil shale ash (OSA)-based cementitious matrix was investigated using the double cantilever beam (DCB) test. OSA replaced cement at 0 %, 10 %, 15 %, and 35 % to reduce carbon emissions and improve the mechanical properties of fibre-reinforced concrete. The basalt fibres were oriented vertically, perpendicular to the fracture plane, and aligned with the loading direction to facilitate accurate assessment of the pull-out mechanisms during crack initiation and propagation. The DCB test involved two notched concrete beams joined by a thin fibre-reinforced layer, which enabled controlled crack opening. Specimens with varying OSA content were evaluated for peak load, fracture energy, interfacial bond strength, and fibre pull-out. The results indicated that vertical fibre alignment enhanced load transfer and interfacial resistance, resulting in higher pull-out forces and improved crack-bridging compared to random fibre placement. Incorporating a moderate amount of OSA improved fracture performance by strengthening the matrix–fibre interface and promoting more ductile failure. Specifically, 10–15 % OSA produced notable improvements in fracture resistance and fibre–matrix bonding, shifting the failure mode from brittle, matrix-dominated to a more ductile, pull-out–controlled process. On the contrary, 35 % of OSA reduced the strength of the interfacial bond due to matrix dilution. Force–displacement curves demonstrated that optimally modified mixtures dissipated more energy and delayed crack propagation. Post-test examination of fibres and force–displacement data confirmed a transition from brittle fracture to gradual pull-out, primarily attributed to enhanced fibre–matrix adhesion. In general, OSA-modified matrices with vertically aligned basalt fibres demonstrated significant potential for developing durable, high-strength, and crack-resistant cementitious composites.

Keywords: *Basalt fibres, double cantilever beam test, fibre–matrix interface, fracture mechanics, oil shale ash, pull-out behaviour.*

1. INTRODUCTION

Fibre-reinforced concrete (FRC) has attracted considerable interest due to its ability to mitigate the inherent brittleness of conventional concrete. Over time, microcracks can develop and spread in concrete, potentially compromising structural integrity [1]–[6]. The incorporation of fibre enhances tensile strength, durability, and crack resistance, thereby improving the sustainability of structures subjected to variable loading conditions. Achieving optimal performance requires a complete understanding of the relationship between fibre orientation, pull-out length, and crack opening [7]–[12]. Although numerous studies have investigated single fibre pull-out behaviour, the present research focusses on the pull-out of multiple vertically aligned basalt composite fibres using a double cantilever beam (DCB) configuration [13]–[16]. In this context, a portion of the matrix cement is replaced with oil shale ash (OSA), a by-product of shale combustion with pozzolanic properties, to reduce the carbon footprint of cement production [17], [18].

Although basalt fibre–reinforced concrete and OSA-modified cementitious systems have been individually investigated, limited research exists on their combined effects, particularly in terms of mechanical and fracture performance [19]–[22]. The interaction between fibres and the matrix under fracture-controlled loading remains insufficiently understood [23]–[25]. Given that the strength of FRC is highly dependent on the quality of fibre–matrix bonding, a thorough understanding of pull-out resistance and crack-bridging mechanisms is essential for the design of reliable structural materials [26]–[28].

Recent advances in sustainable concrete technology have demonstrated the potential of combining industrial by-products with innovative reinforcement strategies to develop high-performance composites [29]–[33]. These developments facilitate the creation of durable and environmentally responsible construction materials suitable for advanced structural applications

The primary objective of this research is to experimentally evaluate the influence of oil shale ash on the fracture behaviour and interfacial bonding performance of basalt fibre reinforced concrete. The results aim to provide robust scientific information on the mechanical viability of combining basalt fibres and OSA, thereby facilitating the development of high performance, durable and sustainable concrete composites for advanced structural applications.

2. MATERIALS AND METHODS

Ordinary Portland cement (CEM I) was the main binder in all concrete mixes, with compressive strengths of about 20 MPa after 2 days and 50 MPa after 28 days. Oil shale ash (OSA), a by-product of combustion, was used to replace 10 %, 15 %, and 35 % of the cement by mass. The OSA particles ranged from 55 µm to 500 µm, with a typical size of about 20 µm, so they acted as both a micro filler and a pozzolanic material.

The basalt fibres were produced from continuous basalt yarn and treated with epoxy resin and hardener to enhance their strength and bonding characteristics. Following curing, the fibres were cut to a standard length of 48 mm. Basalt fibres were selected for their high strength, chemical and thermal resistance, and environmental sustainability. Table 1 shows the concrete mixture ingredients and their proportions.

Table 1. Concrete Mixture Proportion

Ingredients	G3-1	G3-2	G3-3	G3-4
Cement CEM1 (kg)	7.625	7.625	7.625	7.625
OSA (Kg)	0 (0 %)	0.76 (10 %)	1.145 (15 %)	2.67 (35 %)
Water (L)	5	4.25	4.25	5.25
Gravel 4-8 mm (Kg)	26.15	26.15	26.15	26.15
Sand 0.3-2.5mm (Kg)	15.1	15.1	15.1	15.1
Sand 0-1.0 mm (Kg)	2.85	2.85	2.85	2.85
Dolomite flour (Kg)	2.05	2.05	2.05	2.05
Plasticizer D 190 Sika (L)	0.25	0.25	0.25	0.35

The cement content was initially established at 7.625 kg per batch and was proportionally reduced with increasing OSA content. The coarse aggregate was fixed at 26.15 kg and fine aggregate at 17.95 kg. Dolomite flour was maintained consistently at 2.05 kg. The plasticiser content ranged from 0.25 to 0.35 L, and the water content varied from 4.25 to 5.25 L, depending on the OSA proportion. Aggregates, dolomite flour, water, and plasticiser were added sequentially, followed by an additional 10 minutes of mixing to achieve a homogeneous and stable consistency. Fresh concrete was immediately transferred to moulds for casting.

The concrete was poured into steel moulds measuring 40 cm x 20 cm. Before casting, the moulds were cleaned and coated with a release agent. The casting process was carried out in layers: a 2 cm-thick base layer was first added, followed by the placement of steel reinforcement bars (36 cm long, 11.4 mm in diameter) symmetrically, 2 cm from the mould edges and the centreline. The second layer of concrete was poured to cover the reinforcement. The basalt fibres were positioned horizontally within the central fracture zone, 1.5 cm apart and 1.5 cm from the top surface, extending approximately 7 cm from the bottom. A final layer of concrete was added and the second set of steel reinforcement bars was placed in a mirrored arrangement relative to the lower layer. Figure 1a shows the pouring and preparation of the matrix, and Fig. 1b shows the addition of the basalt fibre.

The specimens were compacted with mechanical vibration to remove air bubbles. The moulds were covered with transparent plastic sheets to retain moisture and left for 48 hours. After being removed from the moulds, the specimens were placed in water and cured for 28 days prior to testing.

DCB tests were carried out on a Zwick Z150 electrohydraulic universal testing machine at a constant loading rate of 3 mm/min. As the load increased, cracks formed and spread in the concrete, and when the crack reached the fibre-reinforced area, the basalt fibres were pulled out naturally during the same test. There was no separate pull-out test. Figure 2a shows the double cantilever beam testing, and Fig. 2b shows the specimens after testing.

(a) (b)

Fig. 1. (a) Pouring and preparation of the matrix and (b) addition of the basalt fibre.

(a) (b)

Fig. 2. (a) Double-cantilever beam testing and (b) specimen after testing.

A non-contact video extensometer continuously recorded crack opening, fibre pull-out, and force–displacement data. The resulting load-displacement curves captured the complete fracture process, including matrix cracking, fibre bridging, gradual debonding, and final fibre removal. This testing approach allowed for direct measurement of fracture resistance, energy dissipation, and fibre–matrix bonding within a single experiment.

3. RESULTS AND DISCUSSION

The mechanical behaviour of basalt fibre reinforced concrete incorporating oil shale ash (OSA) was evaluated using the double cantilever beam (DCB) setup. This method facilitated the simultaneous observation of crack initiation, propagation, and fibre pull-out under controlled conditions. The force–displacement results demonstrated that the resistance to fracture and interfacial bonding were influenced by the OSA content. Figures 3–6 show the load–displacement curves of specimens DC1–DC4.

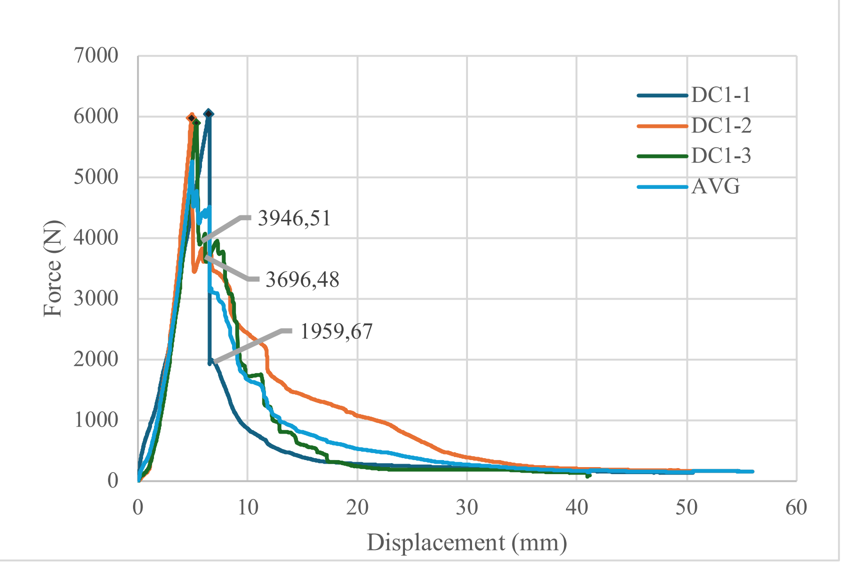

Fig. 3. Force–displacement curves of DC1 specimens.

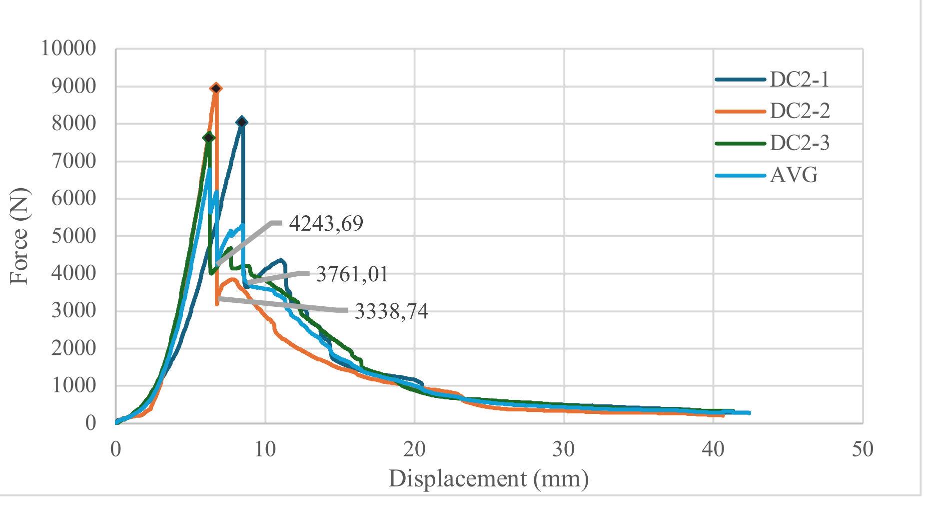

Fig. 4. Force–displacement curves of DC2 specimens.

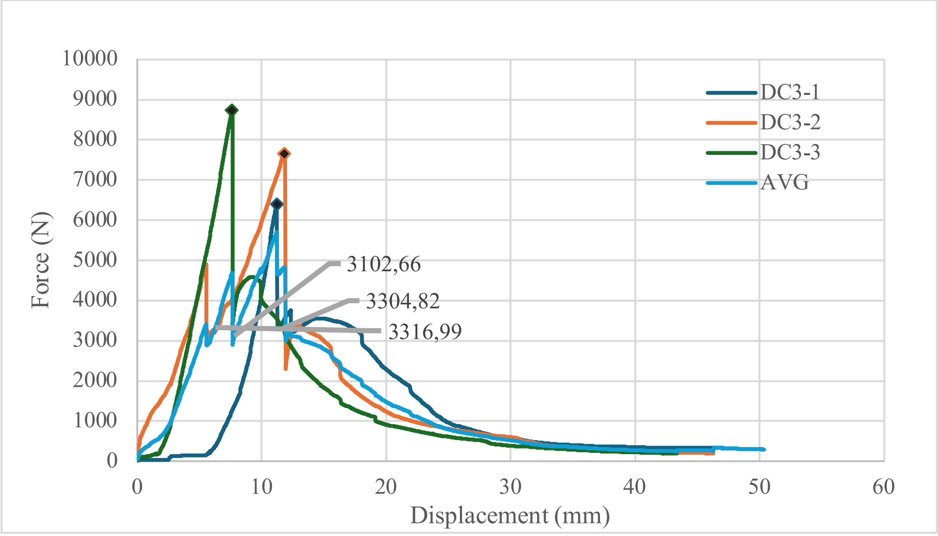

Fig. 5. Force–displacement curves of DC3 specimens.

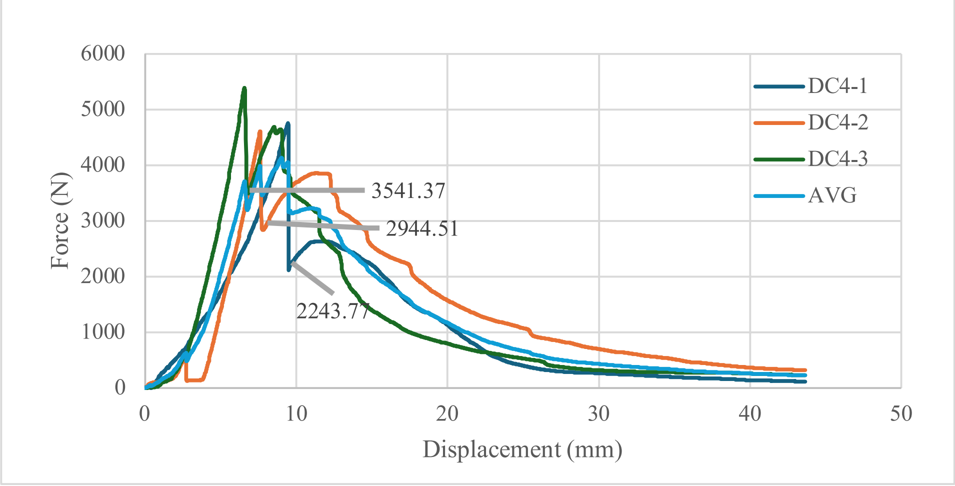

Fig. 6. Force–displacement curves of DC4 specimens.

Control specimens without OSA (DC1) exhibited peak forces for fibre debonding and pull-out ranging from approximately 1959 N to 3947 N, indicating moderate bonding between basalt fibres and cement. With 10 % OSA (DC2), the maximum forces increased to 3339–4244 N, reflecting a significantly improved fibre–matrix bonding and crack-bridging capacity. The 15 % OSA specimens (DC3) demonstrated a similar but more stable response, with peak forces ranging from 3103 N to 3317 N, suggesting consistent performance and improved bonding. On the contrary, specimens with 35 % OSA (DC4) exhibited lower peak forces, from 2244 N to 3541 N, indicating reduced bonding strength at higher OSA levels.

The DCB test displacement curves exhibited three distinct stages: an initial linear elastic phase attributed to the matrix, a non-linear phase characterised by crack initiation and fibre bridging, and a final softening phase as the fibres deboned and were pulled out. Specimens containing 10–15 % OSA showed a slower, more gradual post-peak decline, indicating greater energy absorption and more stable crack propagation. On the contrary, the 35 % OSA specimens exhibited a rapid post-peak drop, reflecting reduced crack bridging and lower fracture energy.

Failure analysis revealed that specimens with moderate OSA content predominantly exhibited ductile fractures, characterised by gradual fibre debonding and sliding. This mechanism facilitated continued stress transfer across the crack, thus increasing the fracture energy. On the contrary, both control and high-OSA specimens failed in a more brittle manner, with the fibres contributing minimally after crack initiation.

In summary, replacing cement with up to 15 % OSA provides an optimal balance between mechanical strength and sustainability, significantly enhancing fracture resistance and fibre pull-out without compromising matrix integrity. Higher OSA content may offer environmental benefits but results in reduced mechanical performance, underscoring the importance of careful dosage selection for structural applications.

4. CONCLUSIONS

The study has tested how basalt fibre reinforced concrete with oil shale ash (OSA) behaves during fracture, using the double-cantilever beam method (DCB). In this test, both matrix cracking and fibre pull-out have occurred simultaneously in a single controlled process. The conclusions are based on the measured load – load–displacement curves and the peak pull-out forces.

The control specimens without OSA (DC1) have exhibited maximum fibre pull-out forces ranging from 1959 N to 3947 N, confirming that basalt fibres already make a meaningful contribution to crack resistance and post-cracking load transfer in conventional concrete. When OSA has been introduced at a 10 % replacement level, the maximum pulling forces have increased significantly to 3339–4244 N, indicating a substantial improvement in fibre–matrix bonding and fracture resistance. A similarly stable and consistent performance has been observed for the 15 % OSA specimens, with peak forces ranging from 3103 to 3317 N, demonstrating improved interfacial stability and energy dissipation capacity. On the contrary, specimens incorporating 35 % OSA have shown a reduction in maximum pull-out forces to 2244–35741 N, indicating a clear deterioration in the strength of the interfacial bond at high replacement levels. This decline is attributed to the dilution of cement paste and the reduced availability of hydration products necessary for effective fibre anchorage. These results clearly establish a threshold OSA content range of 15 % to 35 %, beyond which mechanical performance is compromised despite potential environmental advantages.

In general, the findings demonstrate that basalt fibres substantially enhance the fracture resistance and post-cracking behaviour of concrete. The most favourable results for both mechanical strength and sustainability have been achieved with 10–15 % OSA replacement. The DCB test has proven to be effective in capturing the complete fracture process, including matrix cracking, fibre bridging, and gradual fibre removal.

This research demonstrates that the

combined use of basalt fibres and appropriately dosed oil shale ash is an effective strategy to produce sustainable high-performance concrete. When the OSA content is carefully controlled, the resulting composite offers enhanced environmental benefits without compromising strength or reliability, making it a promising option for advanced building and pavement applications.

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