Investigating the Influence of Oil Shale Ash and Basalt Composite Fibres on the Interfacial Transition Zone in Concrete

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Abstract

Concrete, the most widely used building material, is a cementitious composite governed by three phases, namely, cement, aggregates, and the interface between aggregates/fibres and paste, known as the interfacial transition zone (ITZ). The ITZ is the weakest phase in concrete, which is prone to microcracks, thus resulting in the deterioration of concrete. Investigating the ITZ is important to understand and optimize the bond, mechanical behaviour, and durability of concrete, thereby improving its overall performance and service life. This research investigated the ITZ between the basalt fibres (BF) and the paste in concrete incorporating Oil Shale Ash (OSA). Despite dispersed macro fibres improving some mechanical properties, they introduce additional ITZ in concrete, between fibres and paste, that negatively impact others' properties. We aim to verify OSA's impact on ITZ parameters to neglect fibre´s negative factors. The OSA contents (ranging from 10% to 35% by weight of cement) were utilized to partially substitute the cement, while 5.70 kg/m^3 BF content was used. Though OSA has a significantly high content of pozzolanic oxides, OSA cannot be classified as pozzolanic material according to ASTM C618; however, from literature, it is found to exhibit pozzolanic behaviour, which could result in the development of calcium silicate hydrate gels. The ITZ was analysed with scanning electron microscopy images. The mechanical strengths, including compressive and flexural strength, were determined. The results show that the interaction between BFs and OSA improved the ITZ, enhancing the mechanical strength and overall performance of the concrete. The presence of OSA improved bonding and microstructure densification, especially in ITZ, resulting in increased strength of mixes with 10,15 and 20% OSA by up to 10.5%. The higher replacement ratios had a negative impact on mechanical properties as OSA has not reacted entirely and served partly as an inert filler.

Introduction

Concrete, the most widely used construction material, continually undergoes improvements to enhance its strength, durability, and overall performance. One significant area of focus is the interfacial transition zone (ITZ), which forms between the paste and aggregates [1]. Each aggregate develops an ITZ, the paste-aggregate ITZ is considered as the weakest phase of concrete due to the higher porosity and lower cement content in this zone compared with the bulk paste. It is also the zone where the cracks initiate, which propagate and damage the concrete.

Fibres have gained importance as a valuable addition to concrete mixtures, as it govern the mechanical characteristics of the concrete [2], as fibres enhance the bond by mechanically interlocking the matrix and aggregates, reducing the potential for debonding and improving load transfer across the ITZ [3]. Moreover, fibres act as reinforcement within the concrete, mitigating crack propagation and improving the overall durability of the structure. These advantages have made fibres a preferred choice in engineering practices aiming to enhance the performance of concrete. However, despite the positive influence of fibres, a fibre-paste ITZ, similar to paste-aggregate ITZ is formed [4]. The formation of the ITZ occurs as small binder particles exhibit lower packing density when they come into contact with a large surface area, such as the fibre, creating a "wall effect." This leads to increased porosity and the frequency of phases with low modulus, including pores and low-density calcium silicate hydrate (CSH) near the fibres. Furthermore, an elevated content of calcium hydroxide (CH) is a distinguishing characteristic of the ITZ. A study on high-performance FRC revealed similar hardness values in the ITZ between the aggregate and the paste as in the ITZ between the steel fibre and the paste [5].

The incorporation of supplementary cementitious materials (SCMs) has been widely explored to address this weakness and further optimize the ITZ. The SCMs, such as fly ash, slag, silica fume, and metakaolin, offer unique properties that can improve interfacial characteristics. SCMs possess particle sizes and chemical compositions that can enhance the packing, density, and reactivity within the ITZ [6]. By filling voids, providing additional cementitious gel, and optimizing the curing conditions, SCMs reduce porosity and enhance the ITZ's strength and durability.

This article investigates the synergistic effects of basalt fibres (BF) and paste-containing Oil Shale Ash (OSA) on the ITZ of concrete. It explores the mechanisms by which fibres improve bonding and crack resistance while also acknowledging the limitations of the fibre-paste interface. Additionally, the article highlights the role of SCMs in mitigating these weaknesses, optimizing the ITZ properties, and enhancing the performance of concrete structures.

Methodology

Ordinary Portland cement, CEM II 42,5 N from Schwenk cement Latvia, complying with EN 197-1 was used. The dolomite powder (DP), micro silica (MS) and fine aggregates were obtained from Saulkane, Latvia, while the OSA was obtained from Estonia. The average D50 particle size of OSA was 19.0 um. The coated-chopped composite BF from Deutsche Basalt Faser GmbH having a single filament diameter of 13±1 um, length 24 mm, density of 1.9 g/cm^3 and specific breaking strength of 2670 ± 5% MPa were used. To determine the ITZ of concrete incorporating BF and OSA, control concrete having 20 MPa of compressive strength at 28 days was designed, the mix design and proportions are shown in Table 1. The experimental work was conducted in the Concrete Mechanics Laboratory, Department of Theoretical Mechanics and Strength of Materials, Riga Technical University, Latvia. The flow of the experimental work is shown in Fig 1. The mixing of concrete was done in a tilting drum mixer. The required materials were pre-weighted as per mix proportion and were mixed as follows; (1) half of cement, powders and aggregates were dry mixed 2) half of the water was poured into the mixer; (3) remaining cement, powders and aggregates were added; (4) the remaining water and superplasticizer was then added to provide sufficient workability; (5) BFs were spread into the rotating mixer such that a uniform distribution of fibres is achieved. Mixing duration was between 5-10 min in the mixer to obtain homogenous mix. Fresh concrete consistency was measured by a slump test to ensure a target slump of 22-25 mm. The concrete was cast into the moulds and after 24 hours of initial curing under cover moved to water storage. Compressive and flexural strength was evaluated on 28 days old samples. To understand the ITZ of concrete, the microstructural analysis was conducted using scanning electron microscope (SEM).

Table 1: Mix Proportions for 1 m^3 Concrete

Mix	OPC (kg)	OSA	DP	MS	Aggregates (kg)			Water	SP	Fibres
		(kg)	(kg)	(kg)	0-1.0 mm	0.3–2.5 mm	4–8 mm	(kg)	(kg)	(kg)
C	261.18	0.00	228.01	14.37	598.37	997.19	56.94	237.41	6.53	5.70
OSA10	235.06	26.12	228.01	14.37	598.37	997.19	56.94	237.41	6.53	5.70
OSA15	222.00	39.18	228.01	14.37	598.37	997.19	56.94	237.41	6.53	5.70
OSA20	208.95	52.24	228.01	14.37	598.37	997.19	56.94	237.41	6.53	5.70
OSA25	195.89	65.30	228.01	14.37	598.37	997.19	56.94	237.41	6.53	5.70
OSA30	182.83	78.35	228.01	14.37	598.37	997.19	56.94	237.41	6.53	5.70
OSA35	169.77	91.41	228.01	14.37	598.37	997.19	56.94	237.41	6.53	5.70

Figure 1: Flowchart of the experimental work

Important Findings

- The addition of OSA to fiber concrete resulted in an overall improvement in compressive strength compared to the control sample as shown in Figure 2, with the 10% OSA mix achieving the highest compressive strength of 12.5 MPa. Despite OSA's classification as a non-conventional pozzolan, its chemical composition suggests a high likelihood of exhibiting pozzolanic behavior.
- A noticeable trend in compressive strength is observed as OSA content varies from 10% to 35%, showing a decreasing trend in strength. The mixes with 15% and 20% OSA achieved slightly higher compressive strength than the control sample, indicating their potential use. However, higher OSA content led to a loss in strength, attributed to dilution effects and improper compaction, affecting pozzolanic activity and increasing capillary porosity.
- Flexural strength results showed minor fluctuations across different OSA mixes, with no consistent trend. The reinforcing effect of basalt fibers compensated for potential strength reduction caused by OSA, preventing immediate cracking in the bending test. Low standard deviation values for flexural strength suggest consistent performance within each mix, indicating uniform mix proportions and fiber distribution. However, the potential dilution effect and its impact on early and later age compressive strength, porosity, and permeability need to be considered when incorporating high levels of SCMs like OSA.
- The microstructural analysis of concrete containing BF, as shown in Figure 3, reveals a well-bonded interface between the fibers and paste, with the presence of a network of individual fiber-ITZs contributing to overall strength. Fibers exhibit both fracture and peeling phenomena, potentially due to external forces during sample preparation.
- Proper bonding between BF and paste is essential for effective stress transfer, and the bridging mechanism of well-embedded fibers can restrict crack propagation. Secondary deposition of CSH products on BF surfaces indicates interaction with the alkaline cement paste, enhancing fiber-paste interface properties and contributing to improved mechanical performance.
- The addition of OSA results in enhanced bonding between BF and paste, increased hydration products, and the development of CSH on fiber surfaces. The presence of CASH minerals within the fiber-ITZ, attributed to the higher sulfate content in OSA, further improves the overall performance and durability of the composite material.

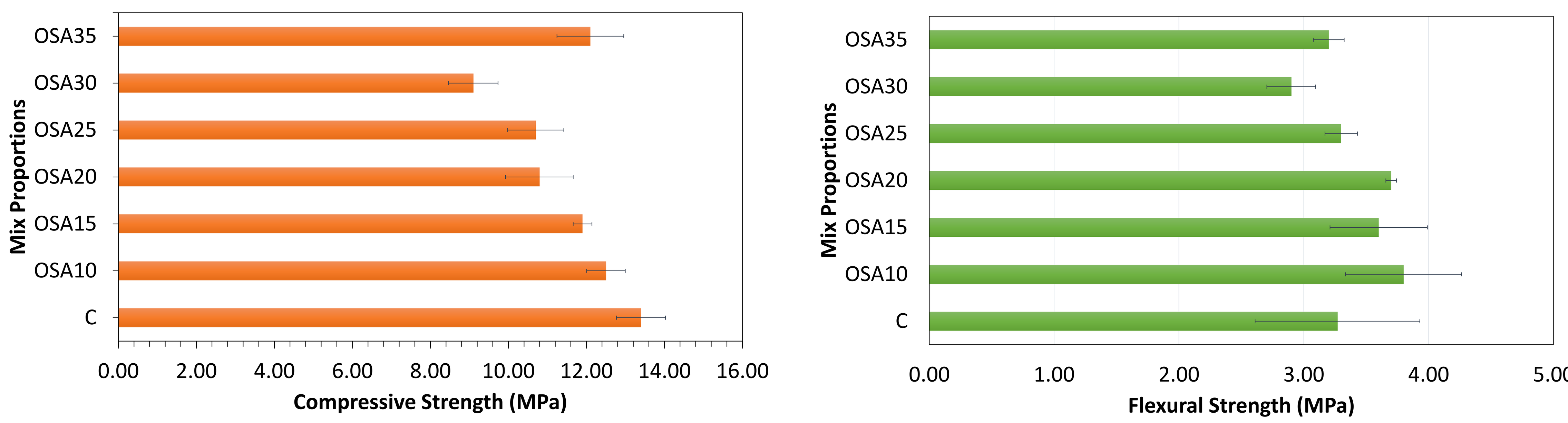

Figure 2: Average Compressive and Flexural strengths of Concrete

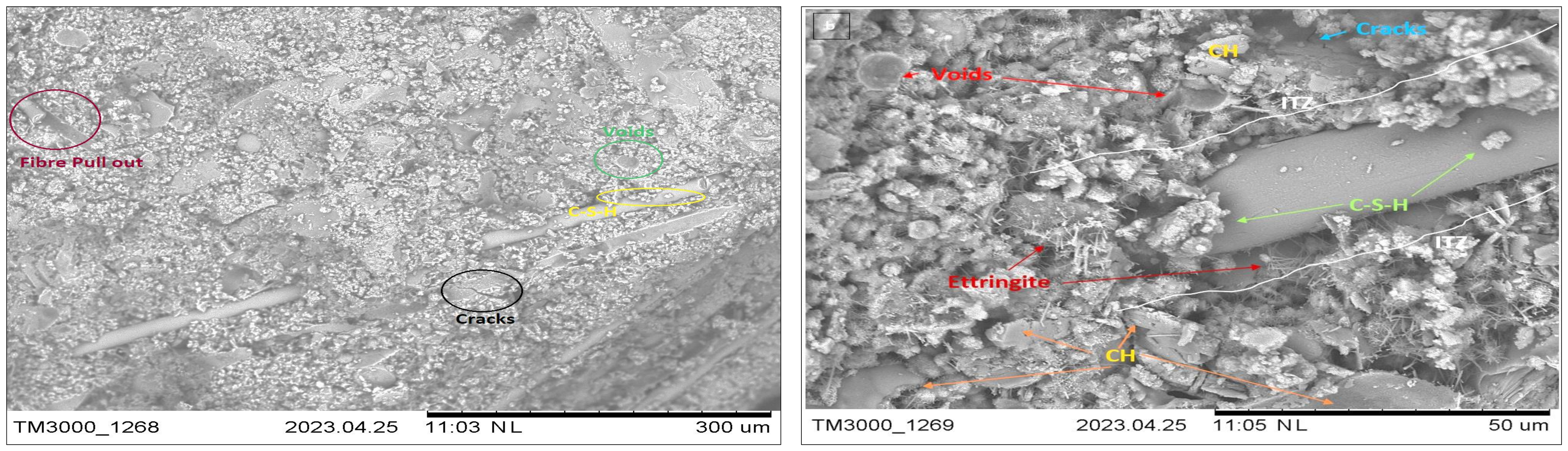

Figure 3: SEM image of illustrating the ITZ microstructure of sample containing BF and OSA at (a) 300 µm and (b) 50 µm

Conclusions

An experimental program was conducted to evaluate the microstructure (fibre and paste ITZ) of concrete mixes containing OSA as a partial replacement for cement and constant content of BFs and subsequent effect on the mechanical strengths. Based on the experimental results, it was concluded that the interaction of BF and OSA in the ITZ leads to improved mechanical characteristics and overall performance of concrete. OSA densifies the microstructure, enhancing interfacial bonding, while BFs reinforce and resist cracking, contributing to increased strength, durability, and crack resistance.

Despite the positive effects, challenges arise from the larger diameter of BFs potentially covering the aggregate-paste ITZ, exposing partial fibers in the bulk paste. The presence of OSA, along with DP and MS, enhances bonding and chemical reactions, improving the ITZ microstructure. However, increasing OSA content results in a dilution effect, reducing compressive strength, while flexural strength remains relatively unaffected due to the compensating reinforcing effect of BFs. Optimal sustainability may be achieved with 15% and 20% OSA mixes.

Further research is essential to optimize the size and distribution of BFs, ensuring effective coverage of the aggregate-paste ITZ without introducing stress concentrations or compromising local integrity. Additionally, investigating various combinations of OSA with other supplementary materials and/or adjusting OSA content can lead to more eco-friendly concrete mixes with enhanced strength and performance, could resolve the dilution effect By addressing these aspects, future studies can pave the way for the widespread and successful application of BFs and OSA as valuable additives in concrete.

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