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Fracture behaviour of bitumen emulsion mortar mixtures

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HIGHLIGHTS

- The bitumen emulsion mortar specimen ductility reaches the maximum after approximately 28 days.
- Three months after the compaction, fracture of all the specimens was clearly brittle.
- The evaluated energy-based parameters were substantially dependent on the viscosity of the bitumen in the emulsions.
- The adhesion between the binder and the aggregate was assumed to emerge faster than the binder's viscosity increased.

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ABSTRACT

The research objective was to evaluate the fracture behaviour of the bitumen emulsion mortar (BEM) mixtures, in terms of their ductility/brittleness, by considering the fracture work and the deformation energy parameters. The specimens with different bitumen emulsions and contents were subjected to the indirect tensile test after 7, 28, and 84 days of curing. The results showed an increase in the specific fracture work over time, while the deformation energy first significantly increased and then decreased to a relatively low level. The deformation energy to total deformation energy-ratio was identified as the most suitable to characterise the fracture behaviour, The adhesion between the binder and the sand in the localised contact regions was assumed to be established faster, which enabled the specimen ductility in the first weeks of curing, while the final binder viscosity achieved by the water evaporation influenced the clearly brittle fracture after three months.

1. Introduction

The primary purpose of considering bitumen emulsion mortar (BEM) mixtures with standardised composition is to evaluate the influence of a bitumen emulsion on mechanical performance of asphalt mixtures. The BEM mixture consists of sand, filler, small amount of cement, and the bitumen emulsion. The composition was standardised by defining the proportions of all constituents and by using the aggregate with exact properties, particle size distribution, and origin [1]. Thus, the variability in the aggregate properties was eliminated, and only the contribution of the considered bitumen emulsion can be evaluated. The bitumen emulsion mortar can also be recognised as a phase in bitumen emulsion bound asphalt mixtures (mostly those for base layers) which comprises the space between the coarse aggregate. The general idea of this approach was based on the method for determining the compressive strength of cement according to EN 196-1 [2] which involves the use of CEN Standard Sand. However, the aggregate mixture concept was additionally modified by adding the filler to provide a mechanical stability necessary to handle and test the specimens.

The Bituminous mixtures of such a composition are commonly referred to as a fine aggregate matrix (FAM) [3] and consider the mixture of bitumen, filler, and sometimes fine aggregate, mostly up to 2 mm [4]. The tests on the FAM have been used for a multiscale evaluation of asphalt concrete mixtures [5–7]. The structural similarity of the FAM materials to the asphalt concrete mixtures enables the measured values to represent the fundamental material properties [6]. Furthermore, it is used to predict the mechanical behaviour with various multiscale and micromechanical models [8–11].

The stability of the bitumen emulsion bound mixtures is built-up by breaking of the bitumen emulsion and coalescence of the formed binder film [12–14]. The water released into the space

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between the aggregate particles is not eliminated immediately from the mixture, but evaporates under the strong influence of the environmental conditions [15]. Consequentially, the water present in the mixture is an important factor for the time development of physical, and mechanical properties of the mixtures [16]. The present knowledge [1] on the physical and the mechanical properties of the BEM mixtures is based on the indirect tensile test and indicates a significant change in the structure and the performance of these mixtures over time. The reason for this is the substantial difference between the mixture in the first week after compaction and few months later.

The clear long-term increase in the stiffness and decrease in the failure strain of the BEM specimens [1] indicates that the time changes in the binder film could also be reflected on their fracture behaviour. The substantial change in the fracture behaviour from ductile to brittle could be visually noticed, but however, it could not be quantitatively characterised by the conventional mechanical parameters of the indirect tensile test. These parameters are based on the point of failure (indirect tensile strength and failure strain) and the 45% of the failure load (stiffness modulus) [17] as well. Although they are very suitable to characterise the mixture performance in general, they are not sufficient to get an insight into the fracture behaviour of the BEM mixtures. Therefore, to characterise the mode of fracture of the specimens it is necessary to consider the load-displacement dependencies integrally. In this regard, the research objectives were the following:

- To evaluate the influence of the bitumen emulsion properties and content on the fracture behaviour of the BEM specimens.
- To identify any changes in the energy-based parameters of the specimen over time related to the fracture work and the deformation energy.
- To explain how the coalescence of the bitumen emulsion and the time-development of the bitumen film affect the observed long-term change in the fracture behaviour.

The fracture characterisation of BEM mixtures would enable to influence the fracture-related performance of the bitumen emulsion bound asphalt mixtures, which could significantly contribute to fundamental knowledge on the binder film development. Moreover, it plays a significant role in producing durable high performance structural materials [18].

2. Experimental method

2.1. Materials

Both the cement and the limestone filler have a positive influence on the micro hardness of the interface between the binder and the aggregate [19]. However, regarding the relatively low cement content, the contribution to the mechanical performance of the mixture was expected to be rather supportive than substantial. The cement hydration significantly contributes to the emulsion stability and breaking [20], although the bitumen droplets could also enclose its particles, and thus, delay the hydration [21,22]. It increases the mixture stiffness by binding the excessive water released by the emulsion breaking, decreases the water sensitivity of the mixture [23], partially neutralises the effect to the emulsifier by increasing the pH value of cationic emulsions, and thus, accelerates the breaking process. Despite the positive effects, the large specific surface of cement and the water consumption by its early hydration products [15] can, in combination with the limestone filler, trigger a premature breaking [24] and decrease workability and compactability of the mixture.

The BEM mixtures were prepared with cationic bitumen emulsions C60B1-BEM [25,26] produced of paving grade bitumen 50/70, 70/100, and 160/220 with the target bitumen content of 60% by mass of the emulsion. Because of its significant influence on the flocculation and the coalescence of the emulsion [27], particle size distributions were also measured by the laser diffraction [28]. The measuring principle was based on measuring the angular variation in the intensity of light scattered as a laser beam passes through the dispersed particulate sample. The properties of the bitumen emulsions used for the mixture preparation and the properties of the recovered bitumen are contained in Tables 1–3, and the particle size distribution diagram is shown in Fig. 1.

Table 1
Properties of the bitumen emulsions.

Designation of the bitumen emulsion	BE1	BE2	BE3
Paving grade bitumen the emulsion was produced of	50/70	70/100	160/220
Perceptible properties (EN 1425)	Brown, liquid, homogeneous		
Breaking behaviour, $BV_{Sikaisol}$ (EN 13075-1)	121	127	129
Mixing stability with cement, S_c (g) (EN 12848)	0.9	0.9	0.9
Binder content, 100% – w (%) (EN 1428)	60.0	60.0	60.0
Residue on sieve 0.5 mm, $R_{0.500}$ (%) (EN 1429)	0.2	0.2	0.1

Table 2
Volume weighted particle size distribution parameters of the bitumen emulsions.

Designation of the bitumen emulsion	BE1	BE2	BE3
10th percentile, d_{10} (μm)	1.165	1.324	1.459
50th percentile, d_{50} (μm)	2.582	2.817	3.235
90th percentile, d_{90} (μm)	7.228	6.949	7.750
Mean (μm)	4.113	3.989	4.381
Mode (μm)	2.316	2.610	3.065

Table 3
Properties of the binder recovered from the bitumen emulsions (EN 13074-1 and EN13074-2).

Designation of the bitumen emulsion	BE1	BE2	BE3
Needle penetration, P_1 (10^{-1} mm) (EN 1426)	54.3	74.8	130.7
Softening point, T_1 (°C) (EN 1427)	50.7	47.9	41.5
Deformation energy, $E'_{0.2}$ (J/cm^2) (EN 13703)[a]	1.11	2.75	1.67
Properties of the RTFOT aged binder			
Change of mass (%) (EN 12607-1)	0.00	−0.01	−0.21
Needle penetration, P_2 (10^{-1} mm) (EN 1426)	38.9	46.1	89.4
Softening point, T_2 (°C) (EN 1427)	53.7	52.9	45.0
Perceptual share of retained penetration (%) (EN 12607-1)	71.7	61.6	68.4
Change of the softening point (°C) (EN 12607-1)	3.0	5.0	3.5

[a] Having regard to the bitumen grades the emulsions were produced of, the test was performed at 15, 10, and 5 °C, respectively, as at the lowest temperatures the measuring was feasible.

The BEM mixtures with three different bitumen emulsions and contents were tested. The sand used for the mixtures contained approximately 80% of SiO_2, had the upper sieve size of 2 mm, and the particle size distribution close to EN Standard Sand [2]. The filler contained approximately 90% of $CaCO_3$. The compositions of the evaluated BEM mixtures are provided in Table 4 and the particle size distribution is shown in Fig. 2.

2.2. Specimen preparation

To prepare one cylindrical specimen of 150 mm in diameter and (125 ± 5) mm in height, 4500 g of the mixture was mixed. The mixing was done at (20 ± 2) °C in a bowl by a hand mixer and additionally by a spatula for approximately 2 min in total for each test specimen separately. The mixture was compacted in a mould of 150 mm in diameter between two steel plates of 149.6 mm in diameter on which contact surfaces a filter paper were inserted. The water was enabled to drain through the clearance between the plates and the mould during the compaction. The system was adjusted to make the movement of the steel plates from the both sides of the mould during the compaction possible. The compaction equipment setup is illustrated in Fig. 3.

The compaction began with the constant speed of 20 mm/min until the force of 49 kN (2.77 MPa) was reached. Thereafter, the force was fixed at 49 kN and the mixture was compacted by the constant static load for 3 min from the both sides. This compaction principle is commonly referred to as Duriez compaction method [29], and was simplified compared to the original cyclic compaction approach [17,30].