

Mechanical fracture properties of concrete with lunar aggregate simulant

Stanislav Seitl^{1,2*}, *Petr Miarka*^{1,2}, *Iva Rozsypalová*², *Katka Pokorná*², *Zbyněk Keršner*², *Jacek Katzer*³ and *Paweł K. Zarzycki*⁴

¹Institute of Physics of Materials, Czech Academy of Sciences, Žitkova 22, Brno 602 00, Czech Republic,

²Faculty of Civil Engineering, Brno University of Technology, Veveri 331/95 Brno 602 00, Czech Republic

³Faculty of Geoengineering, University of Warmia and Mazury in Olsztyn, Heweliusza 4, 10-720 Olsztyn, Poland

⁴Faculty of Civil Engineering, Environmental and Geodetic Sciences, Koszalin University of Technology, Śniadeckich 2, 75-453 Koszalin, Poland

Abstract. From the volumetric point of view, aggregate is the most important ingredient in any kind of concrete. It is impossible to use raw soil instead of aggregate to produce concrete. There are numerous reasons for not using soil for concrete production on Earth, and we should not use lunar soil for concrete production on the Moon for the same reasons. Nevertheless, almost all developed lunar concrete-like composites, such as sulphur or polymeric concretes, are based on raw lunar soil. In the research programme, cement composite based on lunar aggregate simulant was tested. The mechanical fracture properties of the composite were the key point of interest. It was proven that the tested lunar concrete is characterized by stable and uniform properties. The obtained results were compared with the properties of other ordinary cement composites.

1 Introduction

Ever since American astronauts went to the Moon in 1969, scientists have discussed the possibility of establishing a permanent human presence there. The success of Moon colonization will depend on lunar construction efforts [1]. Since human experience with civil engineering and building materials is limited to Earth, we do not have any convincing evidence that the lunar construction industry and structural engineering will be significantly different elsewhere [2-4]. On Earth, concrete is the cheapest, most flexible, strongest and most commonly used construction material. The production volume of concrete exceeds one cubic metre per person per year. Over the years, numerous research teams have dedicated their scientific efforts to the development of original methods of creating concrete-like composites on the Moon [5, 6]. Multiple lunar concrete-like composites (e.g. sulphur concrete, polymeric concrete, and 3-D printed concrete [7]) have been created. All of the proposed composites are very interesting, but they are based on harnessing lunar soil. The

* Corresponding author: seitl.s@fce.vutbr.cz, seitl@ipm.cz

surface of the Moon is covered with a debris blanket, called regolith. It was produced by countless impacts of meteorites over millions of years. It ranges from fine dust to blocks several meters across. The fine-grained fraction is usually referred to as lunar soil [6]. In the authors' opinion, lunar concrete should be based on aggregate in the same way as terrestrial concrete is based on aggregate. Raw lunar soil should be rejected as a material for the production of concrete. A reasonably simple technique for producing lunar aggregate was proposed by Katzer and Zarzycki [8]. The technology is based on targeting only one of the minerals in lunar soil. Ilmenite (the titanium-iron oxide), which is commonly present in both lunar regolith and Earth rocks, was chosen as the perfect candidate for lunar aggregate. The utilization of lunar aggregate for the production of lunar concrete would enable the harnessing of all good practices developed over the last 200 years by the construction industry. All commonly used destructive and non-destructive testing methods, as well as quality control procedures, could then also be feasibly pursued on the Moon [9]. There is no doubt that lunar concrete-like composites based on ilmenite lunar aggregate would be superior (both in terms of mechanical properties and endurance) over composites created using raw lunar soil. One also has to keep in mind that lunar concrete, apart from bearing static loads, will also be exposed to radiation and dynamic loading caused by meteorite impacts. Ilmenite, which is a heavy mineral, is characterized by much higher radiation resistance [10] in comparison to raw lunar soil. Thus, using ilmenite aggregate for concrete production would result in a composite characterized by significantly higher radiation resistance than concrete based on raw lunar soil.

Keeping all the above facts in mind, the authors conducted a research programme focused on cement composite based on the lunar aggregate simulant (LAS). The technique for the preparation of the LAS and the static mechanical properties of the cement composite in question were described in a separate publication by Zarzycki and Katzer [8, 11]. The aim of this contribution is to evaluate the mechanical fracture properties of concrete with the LAS. The investigated and compared properties were as follows: density, flexural strength, compressive strength, modulus of elasticity, fracture toughness, specific fracture energy, and basic fatigue properties expressed by the Wöhler curve.

The recommendations for building a structure are listed in Eurocode 2 [12]. The most relevant part of these recommendations concerns the properties of the used quasi-brittle materials. Measurements and an evaluation of the mechanical fracture properties of the composite in question were conducted according to suggestions made by Karihaloo [13], Bažant [14], Shah [15] and RILEM [16]. Advanced methods were harnessed for the evaluation of material properties such as specific fracture energy and fatigue resistance [18-21].

2 Material and specimen preparation

The density, loose bulk density, and median diameter [17] of the LAS were $4.700 \text{ kg}\cdot\text{dm}^{-3}$, $2.413 \text{ kg}\cdot\text{dm}^{-3}$ and 0.193 mm , respectively. The analysed mixture composition mirrored the standardized mortar used for the testing of cements. The mixture composition was as follows: Portland cement (450 g), water (225 g), standardized sand (1350 g). Due to the higher density of the LAS in comparison to standardized sand, the amount of the LAS added (to match the volume of standardized sand when adding 1350 g) was 2395 g. For the first 24 hours of curing, all specimens were kept in steel moulds covered by a glass sheet. Subsequently, they were removed from the moulds and tightly wrapped in polyethylene sheeting. The specimens were stored at a temperature of $+21 \text{ }^\circ\text{C} \pm 1 \text{ }^\circ\text{C}$. Tap water and CEM 42.5 were used to create the composite in question.

The specimens for the fracture tests had nominal dimensions of $40 \times 40 \times 160 \text{ mm}$ and were notched at midspan (6 specimens to $1/10$ and 6 specimens to $1/3$ of the height).

3 Methods

The experimental measurement of mechanical fracture properties started at the 224th day of curing due to the time consuming nature of the execution of fatigue tests. The specimens were subjected to three-point bending with a span of 140 mm (see Fig. 1 left). During the test, the force vs deflection relationship was recorded at midspan, along with force vs crack mouth opening displacement. After the processing of the collected data, the static modulus of elasticity, effective fracture toughness, effective toughness and specific fracture energy were determined using the Effective Crack Model and the Work-of-Fracture method [13]. After the fracture experiments were performed, compressive strength values were determined using the remaining halves of the specimen (Fig. 1 right).



Fig. 1. Loading configuration used for the fracture testing of specimens in three-point bending (left), and for the subsequent compression test (right).

The specimens were fatigue loaded using a three-point bending test setup with the relative notch length $a/W = 0.1$ (the depth of the notches was 4 mm). The fatigue tests were carried out using a computer-controlled servo-hydraulic strength machine under load control. The utilized experimental setup is presented in Fig. 2 (right). During all the experimental procedures, the temperature and relative humidity were monitored and maintained at 22 ± 2 °C and $50 \% \pm 2 \%$, respectively. The stress ratio R (defined as the quotient of the minimum P_{\min} and maximum P_{\max} load of a sinusoidal wave in each cycle) was 0.1. The load frequency used for the fatigue tests was 10 Hz. The fatigue endurance limit was determined on the basis of an $S-N$ curve (Wöhler curve) [19]. The limit of 2×10^6 cycles to fracture was used to consider the applied stress amplitude as safe for loading during the whole component lifetime [22].

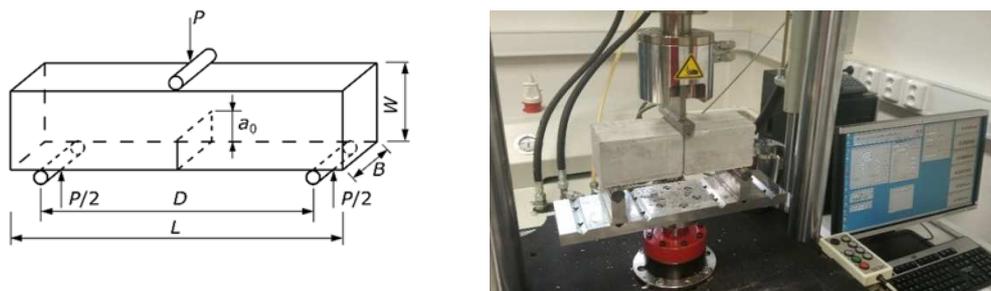


Fig. 2. Geometry of the specimen used for fatigue tests (left) and experimental setup (right).

The employed laboratory technique based on the application of cyclic loading with a defined stress amplitude S to determine the number of cycles N to the fracture of specimens was thoroughly described by the authors in previous publications [18-21].

The formula for fitting the experimentally obtained data from the fatigue test used in this research programme is based on empirically derived $S-N$ diagrams (Wöhler curves):

$$S = AN^B, \tag{1}$$

where:

A, B are the material constants characterising the $S-N$ curve.

The fatigue properties of a heterogeneous material are far from ideal and the experimentally obtained results are usually relatively scattered. Therefore, it is necessary to determine not only the analytical expression but also the index of dispersion $R2$.

4. Results and discussion

The density of hardened cement composite based on the LAS after 28 days of wet curing was equal to $3.290 \text{ kg}\cdot\text{dm}^{-3}$. Before fatigue tests (after 224 days of curing), the bulk density of dry hardened cement composite based on the LAS was equal to $3.056 \text{ kg}\cdot\text{dm}^{-3}$.

The compressive strength at the start of the campaign of fatigue experiments was 39.4 MPa. At the end of the campaign, the compressive strength was 41.5 MPa. The achieved mechanical fracture parameters are listed in Table 1, 2, 3, and 4, which present the values obtained for the modulus of elasticity, effective fracture toughness, effective toughness and specific fracture energy, respectively. The tables include basic statistical evaluations such as: mean value (MV), standard deviation (SD) and coefficient of variation (CV). The values gained for specific fracture energy G_F vs relative notch depth a/W are shown in Fig. 3 with an adequate approximation regression function.

Table 1. Modulus of elasticity in GPa (CV in %).

Specimen	Value	MV	SD	CV	MV	SD	CV
SC3	36.0	30.8	5.17	16.8	28.9	4.96	17.2
SC4	24.1						
SC8	27.2						
SC9	35.5						
SC18	30.9						
SC22	29.2	25.7	2.98	11.6			
SC23	24.3						
SC25	23.8						

Table 2. Effective fracture toughness in $\text{MPa}\cdot\text{m}^{1/2}$ (CV in %).

Specimen	Value	MV	SD	CV	MV	SD	CV
SC3	1.043	0.819	0.18	22.1	0.744	0.18	24.0
SC4	0.635						
SC8	0.633						
SC9	0.915						
SC18	0.871						
SC22	0.511	0.620	0.10	15.4			
SC23	0.662						
SC25	0.687						

Table 3. Effective toughness in $\text{N}\cdot\text{m}^{-1}$ (CV in %).

Specimen	Value	MV	SD	CV	MV	SD	CV
SC3	30.2	21.9	6.27	28.6	19.6	6.55	33.5
SC4	16.7						
SC8	14.7						
SC9	23.6						
SC18	24.5						
SC22	9.0	15.6	5.85	37.4			
SC23	18.1						
SC25	19.9						

Table 4. Specific fracture energy in $\text{J}\cdot\text{m}^{-2}$ (CV in %).

Specimen	Value	MV	SD	CV	MV	SD	CV
SC3	49.1	46.5	5.97	12.8	46.5	4.93	10.6
SC4	44.8						
SC8	37.2						
SC9	48.8						
SC18	52.9						
SC22	45.4	46.4	3.72	8.0			
SC23	50.5						
SC25	43.3						

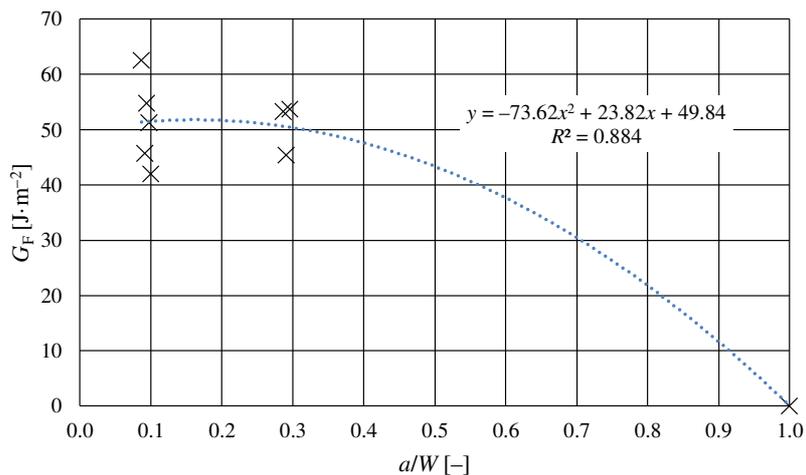


Fig. 3. Specific fracture energy G_F vs relative notch depth a/W .

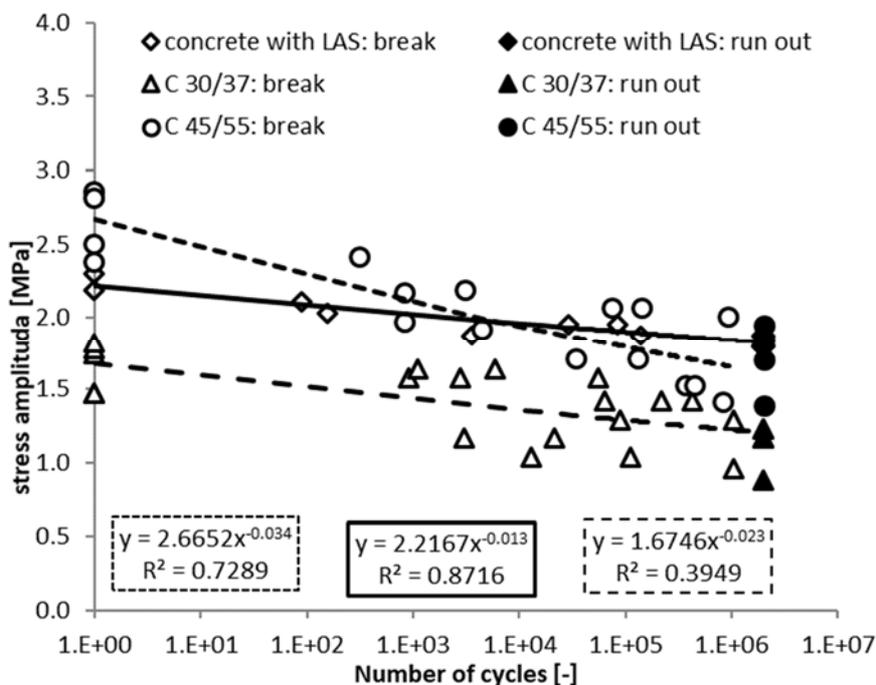


Fig. 4. Comparison of fatigue curves for C30/37, C45/55 and concrete with the LAS.

The experimentally obtained fatigue results for concrete with the LAS are shown in Fig. 4, where the bending stress amplitude [MPa] applied during the fatigue experiments is plotted against the logarithm of the number of cycles N to failure or at 2×10^6 cycles (a limited number of cycles for run-outs, i.e. for unbroken specimens).

The achieved results were compared with the properties of other ordinary concretes based on natural aggregate (C 30/37, C 45/55) [20, 21]. The composite with the LAS showed higher mechanical fracture values in comparison to both ordinary concrete mixtures.

5 Conclusion

The mechanical fracture and fatigue properties of concrete with the LAS were measured and analysed. Ilmenite aggregate behaves similarly to natural sand when used for the production of cement mixes. The following conclusions can be offered:

The scatter of experimental results for concrete with the LAS is standard and is acceptable in terms of practical use.

The bulk density still diminished over time.

The compressive strength was about 40 MPa.

The investigated concrete showed improved mechanical fracture properties compared to concrete with natural aggregate.

It can be concluded that the concrete with the LAS has lower flexural strength than the C45/55, but on the other hand, higher fatigue resistance, as shown in Fig. 4.

Further research is needed, especially considering durability, large scale elements and the water-tightness of composites based on the LAS.

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