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INFLUENCE OF ACCELERATED AGEING ON PULL-OFF STRENGTH OF CONCRETE PRODUCED WITH RECYCLED CONCRETE AGGREGATE AND BLENDED WITH HEMP FIBERS

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As a result of rising demand for non-renewable resources, high energy consumption, and, most importantly, unfavourable environmental consequences, the construction sector is switching to environmentally friendly products. Some feasible options for developing alternative low-cost, renewable and green materials include the utilization of natural fibers and recycled materials from construction and demolition (C&D) waste. This report summarizes a portion of the experimental research being conducted as part of a bilateral research project: "BIO-based cementitious composites with recycled aggregates (Bio-gates)," performed by teams from Novi Sad's Faculty of Technical Sciences and Vienna's Technical University. This research explores the impact of hemp fibers and recycled concrete aggregate (RCA) on the pull off strength of concrete, cured under normal conditions and subjected to wet/dry cycles (accelerated ageing regime). The obtained results revealed that RCA has no detrimental effect on the adhesive bond, while hemp fibers reduce the pull off strength of concrete to a greater extent. Nonetheless, adhesion to the substrate may be regarded satisfactory for all tested concrete types when the limit values specified in the applicable regulations are taken into account.

Keywords: environmentally friendly products, recycled concrete aggregate, hemp fibers, pull off strength

1 INTRODUCTION

The increased environmental consciousness and the necessity to reduce the building industry's raw material use and CO2 emissions have recently been firmly established in a number of European directives. As a result, the researchers all around the globe are focusing on finding alternative low-CO_2 cementitious materials for replacing traditional binders. In addition, aiming to preserve natural resources, recycled aggregates derived from construction and demolition waste (CDW) are increasingly being utilized as natural aggregates replacements.

A sustainable concrete material can be defined as one that is recycled from existing concrete material or one that is generated by lowering the use of aggregate components, which is the subject of this research. In general, it is desirable to create a novel material with acceptable performance while conserving natural resources. The reduction of coarse aggregates is consistent with some of the sustainable interests and actions, such as "Reuse-Reduce-Recycle," and the use of industrial fibers is consistent with the expansion of agricultural activities and farming success.

Natural fibers such as bamboo, jute, bagasse, date palm fiber, and others are used as a micro-reinforcement of contemporary composites (mortar and concrete), aiming to optimize their energy absorption capacity and crack resistance, tensile and flexural strengths, ductility, toughness, and impact resistance. Natural fibers have also been reported to improve thermal insulation characteristics by lowering thermal conductivity by 30%, potentially lowering a building's heat consumption [1]. Due to its high compatibility in soil and environmental circumstances, hemp plants may grow in many places of the world. According to the reports [2-3], hemp crop area in Europe expanded to 33020ha in 2022. Meanwhile, hemp output increased to 179020 tons, demonstrating that the extensive use of hemp fibers (HF) in cement composites can significantly boost the ductile strength of the composite. Comak et al. [4] discovered that adding HF to mortars boosted flexural strength, as did the addition of 12 mm fiber length and 2-3% hemp fiber. According to Ruano et al. [5], introducing hemp fibers might improve the toughness of cementitious composites as measured by pull-out testing. However, as HF are hydrophilic, they are sensitive to moisture fluctuations, resulting in swelling behaviour [6]. This action would eventually degrade the interfacial bonding, lowering the mechanical characteristics of hemp fiber-reinforced cement-based composites.

Aiming to develop and promote the Republic of Serbia's educational system, the Ministry of Education works closely with other countries and international organizations. International scientific initiatives empower the exchange of stuff in the sphere of professional and technical education. In 2022, the Faculty of Technical Sciences in Novi Sad and the Technical University in Vienna signed a bilateral research project titled "Bio-based cementitious composites with recycled aggregates (Bio-gates"). The project is supported by the Ministries of Austria and Serbia and is planned to last two years. This project aims to develop innovative environmentally-friendly composites in which: 1) the natural river aggregate is substituted by recycled aggregates, and 2) conventional reinforcing rebars are replaced by hemp fibers, derived from the industry.

This report presents a portion of the experimental research that was undertaken. It includes pull strength testing of concrete combined with hemp fibers and made with recycled aggregate concrete as a coarse aggregate. Furthermore, the impacts of accelerated ageing were investigated.

2 MATERIALS AND METHODS

2.1 Materials

Portland cement (PC) from Lafarge cement mill in Beočin, Serbia, was utilized. The cement is characterized by a specific gravity of 3.1 g/cm^3 and Blaine fineness of 4000 cm^2/g.

Following types of aggregate were employed in the study:

- Fine aggregate (natural aggregate, the Drina River, 0/4 mm),
- Coarse aggregate (natural aggregate, the Drina River, 4/8 and 8/16 mm),
- Coarse aggregate (recycled concrete aggregate (RCA), unknown origin, 4/8 and 8/16 mm). Note: water absorptions of fractions 4/8 and 8/16 mm are 5,4 and 4,2%.

Primary bast hemp fibers (Cannabis sativa L) were employed for fiber reinforcement (Fig. 1). Hemp fibers (cut to the length of 10mm – Fig. 2) were chosen as they are commonly utilized as fiber reinforcement in cementitious materials and have a lengthy agricultural history in Europe. Previous research reported the characterization results of hemp fibers (tensile strength up to 900MPa, density of 1500kg/m^3, water absorption 100% after 120min) [7].

Fig. 1. Untreated hemp fibers

Fig. 2. Hemp fibers, cut to the length of 10mm

2.2 Methodology

The experimental study was performed on six different concrete mixtures. The reference mortar (A0) was prepared with natural aggregate (NA) and without fibers as micro-reinforcement. A fraction of coarse NA (50 and 100%, respectively) was substituted for RCA in the following two mixes (A50 and A100). Based on the absorptions of RCA fractions, an additional amount of water was delivered to saturate this type of aggregate. The remaining mixtures (B0, B50, and B100) were blended with hemp fibers while maintaining the same aggregate combinations. Table 1 lists the labels and quantities of each concrete mixture's component components.

Table 1. Labels and component materials for concretes

	m_c	m_w	Δm_{w1}	m_{hrwr}	$m_{na,I}$	$m_{na,II}$	$m_{na,III}$	$m_{rca,II}$	$m_{rca,III}$	m_{hf}	Δm_{w2}
A0	360	180	/	1,80	903,9	379,7	524,3	/	/	/	0
A50	360	180	20,6	1,80	875,5	183,9	253,9	183,9	253,9	/	0
A100	360	180	39,9	1,80	848,9	/	/	356,5	492,4	/	0
B0	360	180	/	1,80	872,5	366,4	506,0	/	/	7,5	18,75
B50	360	180	19,9	1,80	845,1	177,5	245,1	177,5	245,1	7,5	18,75
B100	360	180	38,5	1,80	819,3	/	/	344,1	475,2	7,5	18,75

Note: Δm_{w1} *- additional water used for RCA saturation;*
Δm_{w2} *- additional water used for hemp fibers saturation*

Following tests were conducted on concrete:

- fresh concrete: the entrapped air content, bulk density and slump value,

– hardened concrete: pull off strength.

Concrete slabs 300×300×50 mm was cast to determine pull off strength. One series of slabs (each concrete type) was cured in water, while the second was subjected to the wet/dry (w/d) cycles (after the age of 28 days), i.e. accelerated ageing regime. These specimens were exposed to 10 wet and 10 dry cycles alternately. Wet and dry cycles lasted two days each, for a total of 40 days of ageing. The time required for a specimen to be entirely saturated with water (in the wet cycle) or fully dried (in the dry cycle) was determined by a measurement taken prior to the ageing process. One wet cycle involves submerging the specimens completely in water. The dry cycles involve drying specimens in an oven at 40 °C.

3 RESULTS AND DISCUSSION

3.1 Properties of fresh concrete

The properties of fresh concrete are summarized in the following Table.

Table 2. Properties of fresh concrete

	Bulk density (kg/m^3)	Air content (%)	Slump (mm)
A0	2300	2,2	23
A50	2330	2,1	23
A100	2320	2,2	23
B0	1920	3	10
B50	1910	3,2	12
B100	1880	3,2	13

The addition of fibers reduced the bulk density of concrete by around 20%, independent of the type of aggregate used. The swelling action of water-saturated fibers increased the overall volume of concrete while diluting the solid components (cement and aggregate). Concrete labelled B100, blended with hemp fibers and produced with coarse RCA, can be categorized as lightweight concrete based on the bulk density value of less than 1900kg/m^3.
All concretes blended with hemp fibers are characterized by the higher entrapped air content in relation to the reference concretes without fibers. In addition, the slump value of fiber-reinforced concretes was notably reduced, owing to the optimized fiber–matrix bond.

3.2 Pull off strength of hardened concrete

A direct pull-off adhesion test was used to determine the interfacial adhesion between concrete and an adhesive glue. Adhesion aluminum discs of 50 mm diameter were glued to the concrete surface and left to cure for 24 hours to ensure thorough curing of the glue. The adhesive strength was then measured using a pull-off adhesion tester, and the strength results were recorded along with the type of failure. Five concrete specimens of each group were tested for data reliability. Figure 3 depicts the results.

The reference concrete prepared with NA without fibers displayed superior performance, as expected when it comes to the aggregate used. The substitution of NA with 50% and 100% of RCA, as coarse aggregate, resulted in the strength reduction by 15% and 10%, respectively, due to the inferior mechanical properties of RCA (the presence of less dense and porous mortar adhering to it) compared to NA.

The addition of fibers to the concrete mix reduced the composite's pull off strength. In comparison to the corresponding concrete mixtures, the registered strength decreases for concrete types B0, B50, and B100 were 20%, 35%, and 36%, respectively. This decrease can be related to the "dilution" effect, which was observed during the bulk density testing phase of fresh concrete.

Water saturated fibers, dispersed in the concrete mix, diluted it and decreased its bulk density, lowering its mechanical characteristics.

All concrete types without fibers gained strength after wet/dry cycles. The strength increases of A0, A50, and A100 in comparison to the corresponding values were 22%, 15%, and 17%, respectively, as a result of carbonation (the conversion of $Ca(OH)_2$ into $CaCO_3$). Carbonation alters the pore structure of concrete, increasing the density of the pore structure and so enhancing the concrete strength, notably its surface hardness. According to some studies, accelerated carbonation procedures can trigger the reaction of unhydrated cement, boost the early strength of the mixture, and prevent heavy metal leaching [8]. The accelerated ageing regime had less of an effect on the strength of fiber-reinforced concrete. Within this group of concretes, B50 and B100 demonstrated 9% strength gains, whereas B0 exhibited a 3% strength decrease.

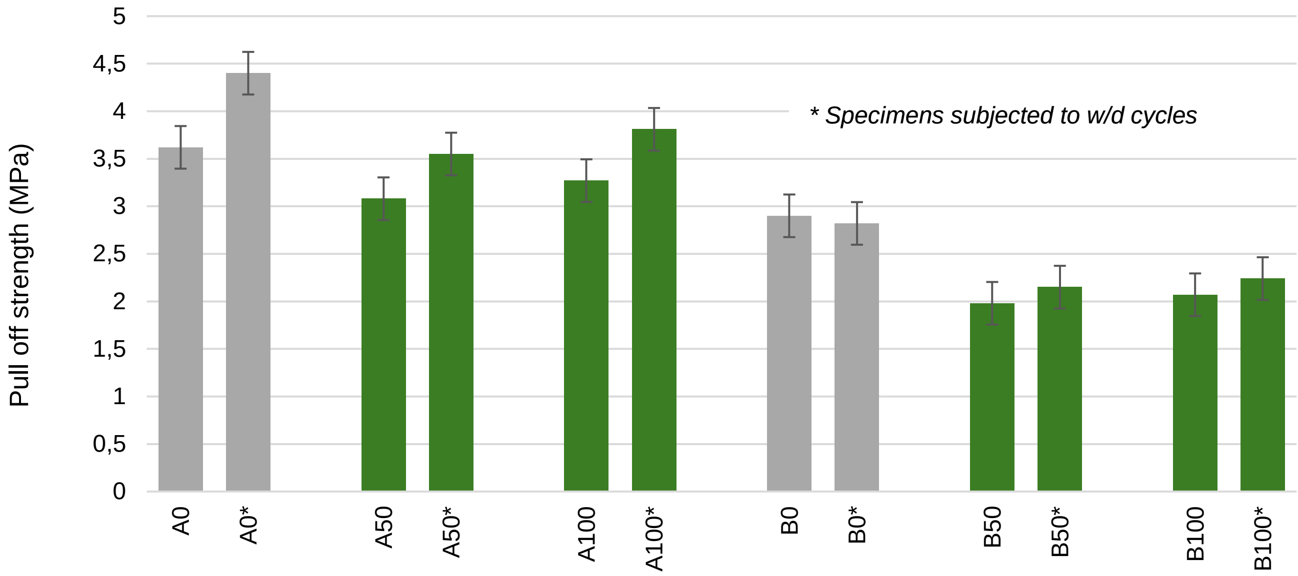

Fig. 3. Pull off strength of different concrete types

The potential fracture patterns can be categorized into three types: (a) adhesion fracture: a fracture at the concrete-glue interface, with a test equal to the adhesive strength; (b) cohesion fracture: a fracture in the concrete itself with higher tensile strength than the adhesive bond; (c) cohesion fracture: a fracture in adhesive glue (this type of failure is unacceptable). Except for A0, all concretes are distinguished by the fracture pattern a, which shows the exact adhesive strength of the concrete.

Recorded fracture patterns are illustrated in Figures 4 and 5 and listed in Table 3.

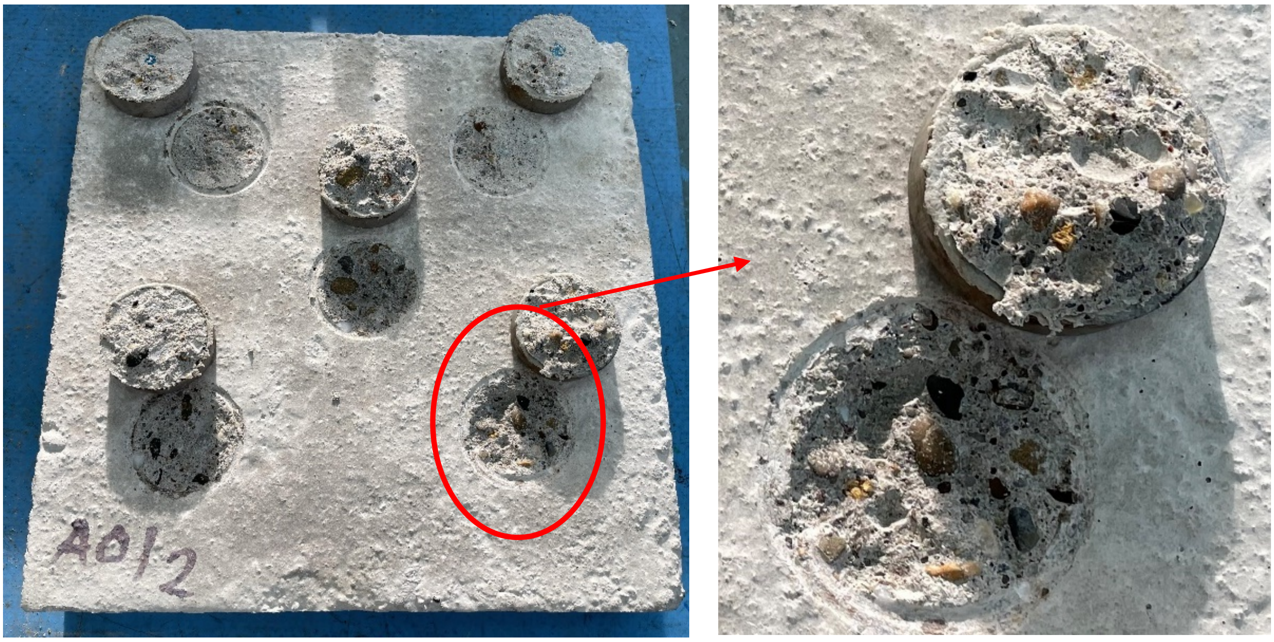

Fig. 4. Testing of pull off strength of concrete; a fracture in the concrete itself

Fig. 5. Testing of pull off strength of concrete; a fracture at the concrete-glue interface

Table 3. Fracture patterns of concretes

	A0	A50	A100	B0	B50	B100
Pattern	b	a	a	a+b	a+b	a+b
	A0*	A50*	A100*	B0*	B50*	B100*
Pattern	a	a	a	a	a	a

The prescribed minimum values of adhesive bond in SRPS EN 1504-3 [9] for structural repair products is 1,5MPa (Class R3). It can be claimed that adhesion to the substrate is appropriate for all concrete types when considering the limit values specified in applicable rules. As the use of RCA has no substantial effect on the adhesive bond, it is possible to produce concrete with this type of coarse aggregate without endangering the composite's quality. On the other hand, it has been demonstrated that hemp fibers reduce the pull off strength of concrete to a greater amount, indicating that their use in this application and property of concrete should be limited.

4 CONCLUSIONS

The aim of the study was to evaluate the effect of using coarse recycled concrete aggregate (50% and 100%) and the addition of hemp fibers (0,5%) on the workability, unit weight, and pull off strength of concrete. The following conclusions can be drawn from this study:

- The addition of fibers reduced the bulk density of concrete by around 20%, independent of the type of aggregate used. The swelling action of water-saturated fibers increased the volume of concrete cast, while diluting the solid components (cement and aggregate).
- All concretes blended with hemp fibers are characterized by the higher entrapped air content in relation to the reference concretes without fibers.
- The slump value of fiber-reinforced concretes was notably reduced, owing to the optimized fiber–matrix bond.
- When natural aggregate was replaced with 50% and 100% RCA as coarse aggregate, the strength was reduced by 15% and 10%, respectively, due to RCA's worse mechanical qualities. The addition of fibers reduced the composite's pull off strength, as a direct consequence of the "dilution" effect. Accelerated ageing via wet/dry cycles generally positively influenced the pull of strength. Except for B0, all tested concretes demonstrated strength improvements, which can be attributed to carbonation effects such as increased pore density and enhanced surface hardness. When the limit values mentioned in applicable standards are taken into account, it is possible to assert that pull off strength is acceptable for all tested concretes.

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