

EXPERIMENTAL PROGRAM FOCUSED ON PUNCHING SHEAR RESISTANCE OF FLAT SLABS CAST FROM CONCRETE CONTAINING RECYCLED AGGREGATES

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Abstract

The article describes an experimental program involving three RC flat slabs cast from concrete with coarse recycled aggregate (CRA). Obtained punching shear capacities are compared with the predictions calculated according to the design model introduced in the 2nd generation of EC2. The test results showed a decrease in the mechanical properties of CRA concrete but did not show a reduction in the punching shear resistance of the slabs. The ratio $V_{R,test}/V_{R,pred}$ yields conservative values of 1.15 and 1.22.

Keywords

Recycled aggregate concrete, punching shear resistance, flat slab, experiment

1 INTRODUCTION

As a result of the extensive construction of buildings and civil engineering structures in Slovakia and abroad, in recent decades a large amount of concrete has been produced [1]. This is associated with a large consumption of natural aggregate (NA), which will cause its shortage in the near future. Using NA is becoming increasingly unfriendly to the environment because it is often necessary to transport it over long distances, which is associated with dustiness, noise, fuel consumption, and therefore a higher price. Researchers are nowadays investigating recycled aggregate (RA) as an alternative to NA. This aggregate is obtained from the demolition waste of old structures. By replacing NA in slabs (high-volumetric structures), it is possible to save up to 1000 kg of NA per 1 m³, i.e. approximately 60% of all aggregate in concrete.

This paper is focused on an experimental program, which investigates the effect of coarse recycled aggregate (CRA) on the mechanical properties of concrete and the punching shear resistance of flat slabs made from coarse recycled aggregate concrete (CRAC). Moreover, the punching shear resistance is compared with the calculated resistance according to the Second generation of Eurocode 2, which allows for the presence of RA in concrete.

Recycled aggregate concrete (RAC)

This paper focuses on coarse recycled concrete aggregate (CRCA), shown on Fig. 1. CRCA is produced by crushing old concrete, separating the reinforcement, and possibly the chemical cleaning of this aggregate, which is finally crushed into the necessary fractions and stored or directly transported for immediate use. RA almost always has worse mechanical properties compared to NA, because cement stones remain stuck on the surface of the aggregate. There are two interfacial transition zones (ITZ) on RA, between the original NA and the cement mortar stuck on this aggregate and between the cement stone and the new cement mortar.



Fig. 1 Coarse recycled concrete aggregate 4/16.

Cement stones have high porosity and often contain microcracks, which cause poorer workability of fresh concrete and increase drying shrinkage. In general, the deteriorated properties of this aggregate are less evident with larger fractions of RA. For this reason, in this experimental program, only coarse recycled aggregate (CRA) is used.

Works focused on punching shear resistance of CRAC flat slabs

This article follows similar works focused on punching shear resistance of CRAC flat slabs, such as [2], [3], [4], [5], [6], [7], [8], [9]. In another publication [10], a comparison of experiments from 2015 to 2022 is described, where researchers verified the punching shear resistance of slabs made from CRAC without shear reinforcement. The following Tab. 1 demonstrates, from the aforementioned publication [10], the punching shear resistance of testing slabs and the mechanical properties of the concrete, which were affected due to the presence of RA in concrete.

Tab. 1 Differences in mechanical properties and punching shear resistance in other works [10] (value after “±” sign represents standard deviation).

Natural aggregate replacement level	Difference in cylinder concrete compressive strength	Difference in modulus of elasticity*	Difference in punching shear resistance
	$\Delta f_{c,cyl}$	ΔE_c	ΔV_{exp}
50%	-8.7% ± 8.7%	-8.2% ± 8.9%	-5.4% ± 7.5%
100%	-11.2% ± 12.0%	-17.3% ± 9.0%	-7.4% ± 10.4%

* Only few articles provided these values

However, in most experiments in reference [10], the thickness of the slabs, which ranged from 50 to 120 mm (half-scale structures), was considered. In experiments described in this paper, the punching shear resistance of flat slabs with a thickness of 250 mm was investigated.

2 METHODOLOGY

The experimental program consists of tests performed on three reinforced flat concrete slabs, in which the punching shear resistance was investigated. The first slab, marked S1.0, is a reference slab without the replacement of coarse natural aggregate (CNA), the second slab had a 50% replacement of CNA, which represents 29% of the total weight of aggregate in concrete. The third slab contained a 100% replacement of CNA, which represents 57% of the total weight of aggregate in concrete. The difference in the concrete recipes of the individual slabs is only in the level of replacement of CNA with CRA. Fine natural aggregate was used with a diameter of 0/4 mm, and CNA and CRA with a diameter of 4/16 mm. CEM II/A-LL 42.5 R cement was used, which is more environmentally friendly compared to commonly used types of cement because in this cement type 6–20% of the clinker is replaced by limestone.

Experimental flat slabs

The dimensions of the slabs are 2.50 × 2.50 m with a thickness of 0.25 m, as shown on Fig. 2. The bending reinforcement consists of steel bars with a diameter of 12 mm in a grid of 100 mm at the top surface. The effective

depth of the slabs was considered to be 218 mm, and the reinforcement ratio of bending reinforcement was 0.52%. Shear reinforcement is not used in the slabs. The column of the flat slab was simulated by a steel plate with a dimension of 300×300 mm. The casting of the three slabs took place at STRABAG in Sered'.



Fig. 2 Reinforcement of the slab S1.2 (left) and concreted slab (right).

Mechanical properties of the concrete

Cubes, cylinders, and prisms were tested in order to determine the mechanical properties of the concrete. Since the slabs were tested approximately 35 days after their casting, which is a relatively short time, the test specimens had to be tested at a very similar time. The concrete strength was determined on five cubes and cylinders and the modulus of elasticity on four prisms.

Tab. 2 Mechanical properties of the concrete.

Slab	Coarse natural aggregate replacement level	Cylinder concrete compressive strength $f_{cm,cyl}$ in MPa	Cube concrete compressive strength $f_{cm,cube}$ in MPa	Modulus of elasticity E_{cm} in GPa
S1.0	0%	39.6 ± 1.0	51.3 ± 1.7	38.8 ± 1.9
S1.1	50%	33.2 ± 1.3	43.2 ± 1.7	31.6 ± 0.5
S1.2	100%	33.4 ± 2.6	44.3 ± 1.3	29.1 ± 0.3

Tab. 2 shows at the level of 50% replacement decrease in the cube and cylindrical strength of concrete by 16% and in the modulus of elasticity by 19%. The 100% replacement scenario showed similar results, the cube strength decreased by 14% compared to the reference concrete and the modulus of elasticity decreased by 25%.

Tests of the slabs

All slabs were tested in the Central Laboratory of the Slovak University of Technology in Bratislava. A well-proven flat slab testing setup was used, consisting of a hydraulic jack under the slab, which pushes the slab upwards, and displacement is prevented by 8 anchor rods with steel plates (hinged supports), which are attached to the rigid reinforced concrete floor of the laboratory. The steel plates simulate the load on a flat slab. The column support is represented by a 60 mm thick steel plate with a size of 300×300 mm. During the tests, the force in the jack, the rotation of the slab, and the deformation of the slab are continuously measured using six linear variable differential transformers (LVDT) and 12 analog deflection gauges. In each loading step, the deformation is verified using photogrammetry. Crack widths were measured and plotted during the individual loading steps.

Punching shear resistance according to Eurocode 2:2023

The punching shear resistance of the slabs is calculated in Eq. (1) according to the Second generation of Eurocode 2 [11]. The partial factors γ_C and γ_V were taken as unity, and instead of f_{ck} , the actual cylinder concrete compressive strengths f_{cm} (mean value) were used.

$$V_{EC2-23} = \tau_{Rd,c} \cdot b_{0,5} \cdot d_v = \eta_\tau \cdot \frac{0,6}{\gamma_V} \cdot k_{pb} \cdot \left(100 \cdot \rho_1 \cdot f_{ck} \cdot \frac{d_{dg}}{d_v} \right)^{1/3} \cdot b_{0,5} \cdot d_v \leq \frac{0,5}{\gamma_V} \cdot \sqrt{f_{ck}} \cdot b_{0,5} \cdot d_v \quad (1)$$

where η_τ (dimensionless), calculated in (2), is a reduction factor taking into account the level of aggregate replacement, k_{pb} (dimensionless) is the punching shear gradient enhancement coefficient calculated in Eq. (3), $\rho = \sqrt{\rho_{Lz} \cdot \rho_{Ly}}$ (dimensionless) is the flexural reinforcement ratio, d_{dg} in m, calculated in (5) and (6), is the size parameter describing the failure zone roughness, $d_v = (d_{vx} + d_{vy})/2$ in m is the effective depth of the slab, b_0 in m is the length of the perimeter of the column, $b_{0,5}$ in m is the critical perimeter at a distance of $0.5d_v$ from the face of the column.

$$\eta_\tau = 1 - 0,2 \cdot \alpha_{RA} \quad (2)$$

$$1 \leq k_{pb} = 3,6 \cdot \sqrt{1 - \frac{b_0}{b_{0,5}}} \leq 2,5 \quad (3)$$

α_{RA} (dimensionless) in Eq. (2) is the substitution rate of recycled concrete aggregates. a_p in m in Eq. (4) is the distance between the centre of the support area and the point of contraflexure in the considered load combination. In the case where a_p is less than $8d_v$, the value of d_v in brackets in Eq. (1) can be replaced with a_{pd} . D_{lower} in mm in Eq. (5) and (6) is the smallest value of upper sieve of aggregate, considered as 16 mm.

$$a_{pd} = \sqrt{\frac{a_p}{8}} \cdot d_v \quad (4)$$

$$d_{dg} = 16 \text{ mm} + D_{lower} \leq 40 \text{ mm} \quad \text{for concrete with } f_c \leq 60 \text{ MPa} \quad (5)$$

$$d_{dg} = 16 \text{ mm} + D_{lower} \left(\frac{60}{f_c} \right) \leq 40 \text{ mm} \quad \text{for concrete with } f_c > 60 \text{ MPa} \quad (6)$$

3 RESULTS

The experiments pointed out very similar punching shear resistances for all three slabs, as shown in Tab. 3. The highest punching shear capacity was achieved in slab S1.1, which contains 50% CNA replacement. The concrete of this slab, together with slab S1.2, reached lower compressive strength of the concrete in comparison with the reference specimen and therefore, it was expected to result in lower punching shear resistance. However, this was not confirmed and higher punching shear resistance of CRAC slabs is considered to be due to the greater roughness of the RA in the shear crack.

Tab. 3 Results of the experimental tests.

Slab	Cylinder concrete compressive strength $f_{cm,cyl}$ in MPa	Coefficient $k_{fc} =$ $(f_{cm,cyl,0} / f_{cm,cyl,i})^{1/3}$ (dimensionless)	Punching shear resistance in the experiment V_{exp} in kN	Ratio of punching shear resistance with coefficient k_{fc} $k_{fc} \cdot V_{exp,i} / V_{exp,0}$ (dimensionless)
S1.0	39.6	1.000	839	1.000
S1.1	33.2	1.061	849	1.074
S1.2	33.4	1.058	847	1.068

Due to the different concrete strengths of the individual slabs, the punching shear resistance of the slabs was compared using by concrete strength normalized resistance of the slabs. For this purpose, the k_{fc} coefficient was calculated. The slabs made of CRAC achieved a higher punching shear resistance than the reference slab in the experiment. Considering the k_{fc} coefficient, the normalized resistance of the RAC slabs increased by 7%.

Tab. 4 Comparison of the test results.

Slab	Punching shear resistance in the experiment V_{exp} in kN	Coefficient considering recycled aggregate in concrete η_τ (dimensionless)	Punching shear resistance acc. to EC2-23 V_{EC2-23} in kN	Ratio test / calculation V_{exp} / V_{EC2-23} (dimensionless)
S1.0	839	1.000	831	1.009
S1.1	849	0.943	739	1.149
S1.2	847	0.885	695	1.218

Tab. 4 shows the value of the coefficient η_τ and the punching shear resistance calculated according to [11]. The coefficient η_τ reduces the calculated punching shear resistance by 6 and 11%, respectively. This is one of the main reasons for the relatively large margin in the calculated resistance compared to the resistance obtained in the experiments.

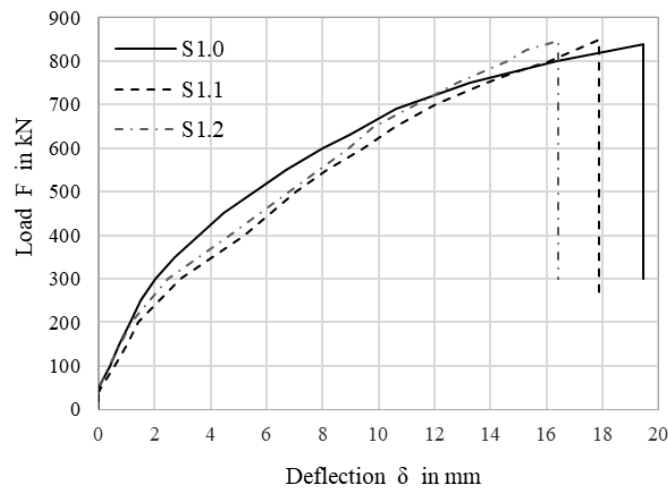


Fig. 3 Load and deflection relationship.

The graph in Fig. 3 shows the relation between the force in the hydraulic jack and the deflection in the middle of the slabs during the tests. The graph shows smaller deformations of the reference slab than the CRAC slabs before transiting to the plastic region of the behaviour of the slab due to the higher modulus of elasticity of the concrete. The unexpected values of the slab deformation at failure were mainly caused by the low flexural reinforcement ratio, where flexural reinforcement started to plasticize before failure. However, all slabs experienced punching shear failure and the differences in the deflections of the individual slabs prior to failure are quite small.

4 DISCUSSION

Experimental results align with findings from studies conducted worldwide, especially that the change in concrete strength does not necessarily coincide with the change in punching shear resistance compared to the reference slab. This can be seen clearly in the large standard deviation of the change in punching shear resistance in Tab. 1. In these experiments, this is evident by the inverse ratio between the change in concrete strength of CRAC and the change in the punching shear resistance of CRAC slabs compared to the reference slab.

The η_τ coefficient, which is set by the EC2 (2023) [11] standard, is certainly up for discussion. This coefficient can reduce the shear resistance of a structure by up to 20%. It should be noted that the standard allows this coefficient to be used in the general calculation of the shear resistance of a structure, however, the standard does not mention its consideration in punching (punching is a two-way shear in the structure, not one way shear).

The calculated punching shear resistance, which considers this coefficient gives a very conservative value. That leads us to the opinion that this factor is not intended to refine the assessed value of $V_{R,c}$, but rather to provide engineers with sufficient safety margin when designing structures with RAC.

5 CONCLUSION

The experimental program and analytical calculations brought the following conclusions:

- when replacing CNA with CRA, a decrease in concrete strength and modulus of elasticity should be expected,
- the decrease in concrete strength due to CNA replacement often does not lead to a decrease in the punching shear resistance of a flat slab cast from CRAC (however, more tests of slabs with an effective depth of more than 200 mm are needed to confirm this finding),
- the proposed η_τ factor by the second generation of Eurocode 2, provides a sufficient safety margin for the design of flat slabs cast from RAC.

Furthermore, it would be appropriate to investigate in more detail aggregate interlocking, which affects the punching shear resistance of flat slabs. For further research, the production of a second series of slabs is planned, which will consider a higher amount of bending reinforcement. In this way, the effect of recycled aggregate on the punching shear strength at higher stress levels will be investigated.

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