ANALYSIS OF THE PUNCHING SHEAR RESISTANCE OF REINFORCED RECYCLED AGGREGATE CONCRETE SLABS ACCORDING TO VARIOUS STANDARDS

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Abstract

This paper presents an analysis of the punching shear resistance of reinforced recycled aggregate concrete slabs. This work mentions several papers focusing on recycled aggregate concrete slabs. Punching shear resistance is assessed according to three design approaches based on standards. This article also describes the design of an experimental programme for the testing of reinforced concrete flat slabs from recycled aggregate concrete. A comparison of the results of analytical calculations and experiments shows that the most accurate design code was the second generation of Eurocode 2 and Model code 2010 with an updated failure criterion when the mean values of the ratio V_{test} / V_{calc} reached 1.15 and 1.14 respectively. On the other hand, the design code followed by Eurocode 2 provided results with higher safety when the V_{test} / V_{calc} ratio was 1.41.

Keywords

Recycled aggregate, punching, concrete slab, standard

1 INTRODUCTION

As the population increases, the need for the construction of buildings and engineering structures increases too. The construction of new buildings creates a large amount of building materials, and consequently, a lot of waste is generated from demolished buildings. The production of natural aggregates worldwide almost doubled from 21 to 40 billion tons between 2007 and 2014 [1]. The biggest credit for this goes to the construction industry. With such a large amount of demand, countries are running out of aggregate stocks, so we are forced to conduct new research into the use of recycled aggregate (RA) in concrete.

Studies have shown that the largest portion of solid waste worldwide is construction waste. The good news is that almost 80% of the construction waste that goes to landfills can be recycled and eventually reused.

Recycled aggregate concrete

We can distinguish 4 types of aggregate according to origin. The most suitable of them for concrete is still natural aggregate. From an ecological and economic point of view, the concrete recycled aggregate seems to be the best substitute. We can obtain recycled aggregate for concrete waste during building repairs or the demolition of buildings and structures.

The obtained material is crushed into smaller pieces, separated from the steel reinforcement and cleanedof possible chemical impurities, then crushed again to the required size, sorted according to grain size and finally stored or immediately used.

In fact, coarse aggregate (CA) makes the largest contribution to the final strength of concrete. That is typical for natural aggregate concrete (NAC). CA in concrete also determines the modulus of elasticity [2]. Cement stone works only as a binder of individual aggregate particles; it helps transfer stresses between aggregates. Therefore, we attribute concrete failure to the failure of the structures of the binder – cement stone.

RA always consists of original natural aggregate and cement sealant, which remains adhered to the aggregate even after the concrete is crushed. Cement sealant contains a large number of pores and is usually weakened by microcracks. This is the main reason for the worse properties of recycled aggregate concrete (RAC) compared to concrete produced from natural aggregate (NA). Pores and microcracks have the effect of reducing the strength and modulus of elasticity of concrete, increasing water absorption and worsening the frost resistance of concrete.

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RA in concrete has received more attention in recent years. While in the previous decades it was mainly used as a base material for buildings or linear structures, sidewalks or as backfill for construction pits, in the last eight years, research into the use of RA in load-bearing structures has become a necessity.

Relevant articles about RAC slabs

In this paper, high attention is paid to works from all over the world in which researchers investigated the punching shear resistance of reinforced concrete flat slabs produced using coarse recycled aggregate (CRA). In all articles, they considered the partial or full replacement of coarse natural aggregate (CNA) (fractions > 4 mm) with concrete CRA. All slabs are without shear reinforcement.

A two-fold approach can be used when using RA. In the first case, with an increase in the percentage of RA, the strength of the concrete is preserved (by adding cement), or the cement content in RAC is preserved at the same level as in NAC. The same cement content was preserved in all articles at all levels of aggregate replacement. This may seem to be a more ecological option. However, in practice, this choice may lead to concrete exhibiting lower strength and a lower modulus of elasticity, which means more reinforcement is needed.

Since 2015, a few articles from around the world about RAC slabs have been published. The present article considers the six most relevant. The authors performed experimental programmes with half-scaled reinforced square slabs with depths between 5 and 12 centimetres. During the experiment, all slabs were supported linearly on four edges or on eight points. Force was applied to the top surface.

Leelatanon et al. [3] tried to compare his experimental study with other studies focusing on the punching shear resistance of RAC flat slabs. For ten slabs he looked at two different flexural reinforcement ratios. Sahoo and Singh [4] compare the punching shear resistance of slabs with the use of RAC for three levels of strength of concrete, Normal – N, Medium – M and High – H. They also describe the strut-and-tie model in detail in the work.

Xiao et al. [5] investigated the increase in concrete strength due to the addition of steel fibres to RAC. He also compared the punching shear resistance of slabs with and without steel fibres. This paper speaks only about RAC slabs without the addition of steel fibres. Francesconi et al. [6] proposed an experimental programme with 12 slabs with dimensions of 1.10 x 1.10 m with a depth of only 50 mm. That limits the effective depth to 35 mm. The article minutely describes numerical analysis according to standards.

Mahmoud et al. [7] focus on RAC strength, separating CRA into two maximum nominal sizes, namely 12.5 and 25.0 mm. For RAC slabs he tracks the differences between the punching shear resistances of the slabs. In the last publication, Reis et al. [8] described the punching shear resistance of 8 slabs from RAC. He also presents a non-linear analysis of slabs used in experiments.

Tab. 1 Input parameters of all experiments.

	CNA replacement level	Slab dimension b x l x h [m]	Dimension of theoret. column b x l [cm]	Average effective depth d [mm]	Flexural reinforc. ratio ρ [-]	Maximum size of CRA d_g [mm]
S. Leelatanon	*0-25-50-75-100*	*1.5 x 1.5 x 0.10*	*20 x 20*	*73*	*0.80* *1.50*	*19.0*
S. Sahoo	*0-50-100*	*1.2 x 1.2 x 0.10*	*15 x 15*	*75*	*1.16*	*12.5*
J. Xiao	*0-30-50-100*	*1.5 x 1.5 x 0.12*	*20 x 20*	*99*	*1.14*	*25.0*
L. Francesconi	*0-30-50-80-100*	*1.1 x 1.1 x 0.05*	*20 x 20*	*35*	*0.56*	*12.0*
Z. I. Mahmoud	*0-30-60-100*	*1.2 x 1.2 x 0.10*	*10 x 10*	*70*	*1.12*	*12.5* *25.0*
N. Reis	*0-20-50-100*	*1.1 x 1.1 x 0.09*	*15 x 15*	*72*	*0.93*	*22.0*
T. Fecko (preparation)	*0-50-100*	*2.5 x 2.5 x 0.25*	*30 x 30*	*204*	*1.01*	*22.0*

In Tab. 1, all input parameters of experiments are summarised. During the test, load was applied by a concrete column connected to the slab or by a steel plate. The dimensions of these theoretical columns are written in Tab. 1.

2 METHODOLOGY

This work is focused on three levels of replacement of CNA. As a reference slab, we can consider a slab with zero percent replacement of CNA in the concrete. Other important levels are 50% and 100%, which means full replacement of CNA. Tab. 2 shows the concrete cylinder compressive strength of those levels. The range of concrete strengths was between 26 to 71 MPa for the reference slabs. We can observe the highest drop in concrete strength in works by Xiao and Francesconi (12–29%).

In the second part of Tab. 2 are summarized the punching shear resistance of slabs with 3 levels of aggregate replacement. The highest drop in slab resistance was in work by Mahmoud 25,0 (-24,1%). The best results, which we wanted to achieve, were attained in work by Sahoo. The punching shear resistance of slabs actually rose after replacing 50 or even 100% of CNA with CRA. Similar results are shown in work by Reis.

Tab. 2 Results of experiments.

	Cylinder concrete compressive strength MPa			**Punching shear resistance of the slabs kN**		
	$f_{c,cyl,0}$	$f_{c,cyl,50}$	$f_{c,cyl,100}$	$V_{exp,0}$	$V_{exp,50}$	$V_{exp,100}$
S. Leelatanon 0.8	*26.5*	*23.5*	*22.3*	*180.0*	*159.8*	*150.4*
S. Leelatanon 1.5	*28.1*	*24.3*	*22.2*	*260.9*	*217.8*	*217.5*
S. Sahoo N	*29.8*	*28.4*	*29.4*	*207.3*	*214.2*	*224.4*
S. Sahoo M	*43.7*	*43.5*	*43.0*	*254.7*	*254.2*	*258.6*
S. Sahoo H	*61.2*	*56.8*	*58.6*	*258.1*	*260.0*	*267.0*
J. Xiao*	*52.3*	*38.9*	*37.1*	*320.0*	*307.1*	*303.4*
L. Francesconi	*71.1*	*62.0*	*50.8*	*68.7*	*66.2*	*70.0*
Mahmoud 12.5**	*37.2*	*32.5*	*31.2*	*157.5*	*137.5*	*122.0*
Mahmoud 25.0**	*39.4*	*34.3*	*33.5*	*172.5*	*140.5*	*131.0*
N. Reis*	*46.8*	*46.6*	*45.6*	*163.3*	*169.2*	*160.1*

* cube compressive strength of concrete
** 60% replacement level of CNA, not 50%

Fig. 1 and Fig. 2 shows changes in the concrete strength and punching shear resistance of slabs due to replacement of CNA.

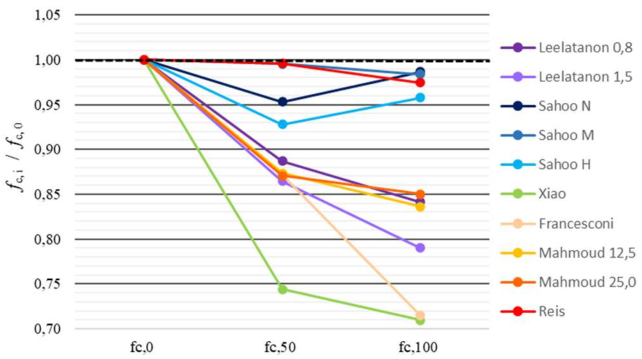

Fig. 1 Change in concrete strength due to replacement of CNA.

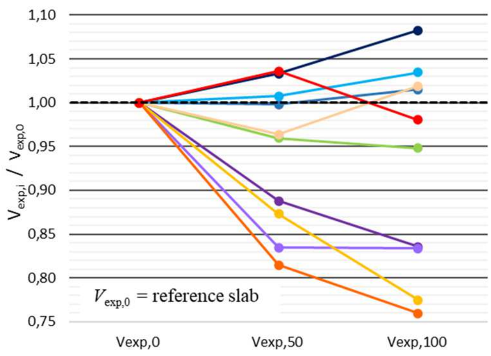

Fig. 2 Change in punching shear resistance of slabs due to replacement of CNA.

The connection between the compressive strength of concrete and punching shear resistance is expected. It applies to works by Sahoo, Reis and Leelatanon. The most different comparison is in the work by Francesconi, where despite a huge drop in concrete strength, the punching shear resistance of the slab remained very similar to the reference slab without CRA. One of the main reasons may be the small thickness of that slab.

Preparation of an experimental programme

The experimental part of my research involves 5 concrete slabs designed with dimensions of 2.50 × 2.50 × 0.25 m, shown in Fig. 3. Compared to other research projects, these experimental slabs will have a thickness that corresponds to the thickness of a real structure.

The differences between the punching shear resistances of the slabs at individual levels of replacement will be investigated. Coarse aggregate with a diameter of more than 4 mm will be replaced. The CRA will be provided by

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two independent suppliers from abroad. The first slab will be a reference slab with zero aggregate replacement. In the other four slabs, 50 and 100 percent of CNA will be replaced.

The required concrete strength class of the reference sample is C30/37. The amount of cement will be retained in the other slabs, which is likely to cause a slight decrease in the concrete strength. All five slabs will be without shear reinforcement and the mainreinforcement bars with a diameter of 16 mm will be used in a 100 mm grid. The slab will be cast upside down due to the position of a 30 x 30 cm column with a height of 30 cm from the bottom side.

All the tests will be carried out in the laboratory of the Slovak University of Technology in Bratislava. The force will be applied to the column from below by a hydraulic jack, and at eight places the slabs will be anchored with bars to the strong concrete floor of the laboratory. During the test, the force pushing on the column will be measured using a load cell. The deformations will also be measured using linear variable differential transformers (LVDT) and mechanical deflection meters, and the rotation of the board using an inclinometer. The cracks will be recordedand their widths measured in every individual load step.

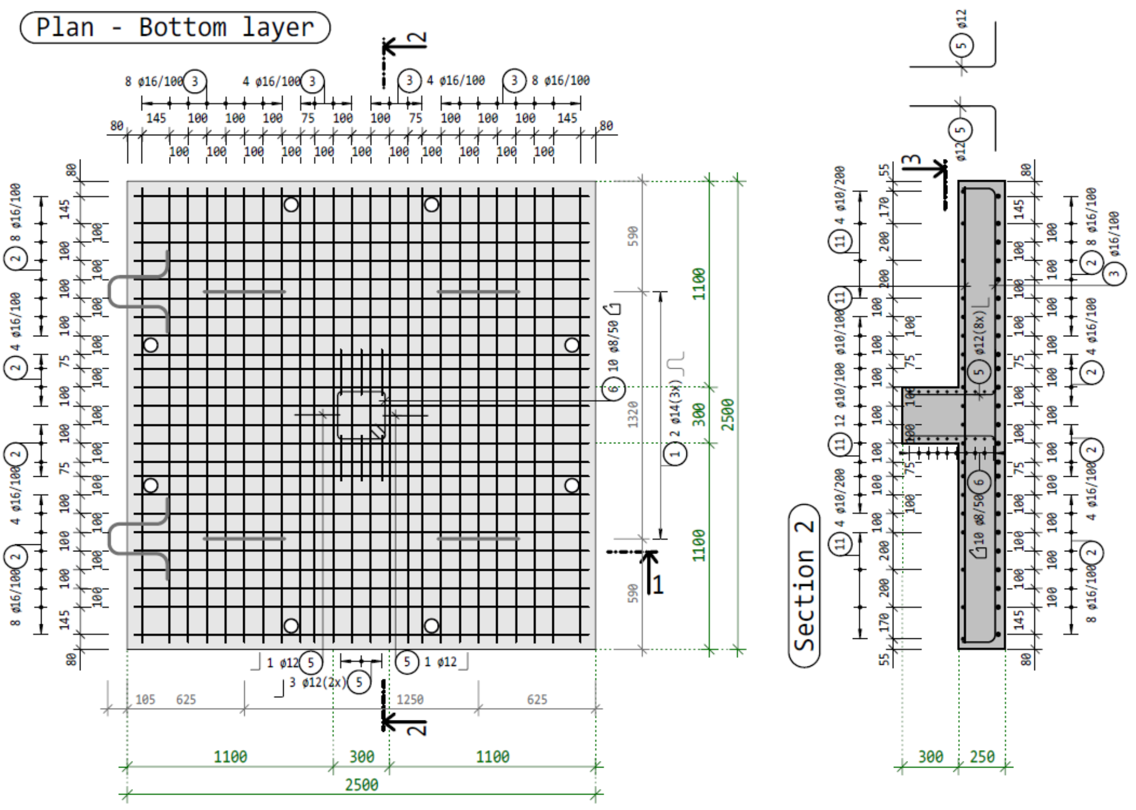

Fig. 3 Experimental slab – dimensions and reinforcement.

Design codes according to standards

This section is focused on calculations according to standards. The results are subsequently compared with a real experiment, so partial factors γ_C and γ_V were taken unity (1). Actual cylinder concrete strength f_{cm} (mean value) obtained from tests was used instead of f_{ck}.

EN 1992-1-1: 2004 (EC2)

According to Eurocode 2, engineers calculate the punching shear capacity of a reinforced slab using Eq. (1) and Eq. (2),:

$$V_{\mathrm{Rd,c}} = C_{\mathrm{Rk,c}} \cdot k \cdot \left(100 \cdot \rho \cdot f_{\mathrm{ck}}\right)^{1/3} \cdot u_1 \cdot d \geq V_{\min} \tag{1}$$

where $C_{\mathrm{Rk,c}} = 0.18/\gamma_C$, $k = 1 + \sqrt{200/d} \leq 2$ is the size parameter (d in mm), $\rho = \sqrt{\rho_{lz} \cdot \rho_{ly}} \leq 0.02$ is the flexural reinforcement ratio, f_c is the cylinder compressive strength of concrete (in MPa), u_1 is the critical perimeter at a distance of 2d from the face of the column, d is the effective depth of the slab.

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$$V_{\min} = 0{,}035 \cdot k^{1{,}5} \cdot \sqrt{f_{\mathrm{ck}}} \cdot u_1 \cdot d \tag{2}$$

Second generation of Eurocode 2 (prEC2)

The second generation of Eurocode 2 provides the following Eq. (3) for the punching shear capacity of a reinforced slab. It allows to take into account the effect of RA in the punching shear resistance of flat slabs made of RAC using a factor η_τ.

$$\tau_{\mathrm{Rd,c}} = \eta_\tau \cdot \frac{0{,}6}{\gamma_{\mathrm{V}}} \cdot k_{\mathrm{pb}} \cdot \left(100 \cdot \rho_{\mathrm{l}} \cdot f_{\mathrm{ck}} \cdot \frac{d_{\mathrm{dg}}}{d_{\mathrm{V}}}\right)^{1/3} \cdot b_{0,5} \cdot d_{\mathrm{V}} \leq \frac{0{,}6}{\gamma_{\mathrm{V}}} \cdot \sqrt{f_{\mathrm{ck}}} \cdot b_{0,5} \cdot d_{\mathrm{V}} \tag{3}$$

where η_τ is a reduction factor taking into account the level of aggregate replacement, k_{pb} is the punching shear gradient enhancement coefficient calculated by Eq. (5), d_{dg} is the size parameter describing the failure zone roughness, $d_{\mathrm{v}} = (d_{\mathrm{vx}} + d_{\mathrm{vy}})/2$ is the effective depth of the slab, b_0 is the length of the perimeter of the column, $b_{0,5}$ is the critical perimeter at a distance of $0.5d$ from the face of the column.

$$\eta_\tau = 1 - 0{,}2 \cdot \alpha_{\mathrm{RA}} \tag{4}$$

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

α_{RA} in Eq. (4) is substitution rate of recycled concrete aggregates. a_{p} in Eq. (6) is the distance between the centre of the support area and the point of contraflexure in the considered load combination. In the case when a_{p} is less than $8d$, we can replace the value of d_{v} in brackets in Eq. (3) with a_{pd}.

$$a_{\mathrm{pd}} = \sqrt{\frac{a_{\mathrm{p}}}{8}} \cdot d_{\mathrm{V}} \tag{6}$$

$$d_{\mathrm{dg}} = 16\,mm + D_{\mathrm{lower}} \leq 40\,mm \qquad \text{for concrete with } f_{\mathrm{c}} \leq 60 \text{ MPa} \tag{7}$$

$$d_{\mathrm{dg}} = 16\,mm + D_{\mathrm{lower}} \left(\frac{60}{f_c}\right) \leq 40\,mm \qquad \text{for concrete with } f_{\mathrm{c}} > 60 \text{ MPa} \tag{8}$$

Model Code 2010 (MC2010)

Model Code 2010 is based on critical shear crack theory. Therefore, there are four approximation levels for the evaluation of the punching shear capacity of a reinforced concrete slab without shear reinforcement. In this paper, level III was used to reach more accurate results. Punching shear capacity is determined by Eq. (9):

$$V_{\mathrm{Rd,c}} = k_\psi \,.\, \sqrt{f_{\mathrm{ck}}} \,.\, b_{0,5} \,.\, d_{\mathrm{V}} \tag{9}$$

where k_ψ is a parameter which depends on the rotations of the slab formulated in Eq. (10), d_{g} is the maximum size of the aggregate, ψ is connected with the rotation of the slab around the supported area shown in Eq. (11) and its value depends on the level of approximation, r_{s} presents the same distance as a_{p} in prEC2, f_{y} is the yielding strength of flexural reinforcement, E_{s} is the modulus of elasticity of steel, m_{E} is the average bending moment in a support strip calculated from the linear elastic model, m_{R} is the flexural capacity of the slab.

$$k_\psi = \frac{0{,}75}{1 + 15 \,.\, \dfrac{\psi \,.\, d_{\mathrm{v}}}{16\,mm + d_{\mathrm{g}}}} \leq 0{,}6 \tag{10}$$

$$\psi = 1{,}2 \,.\, \frac{r_{\mathrm{s}}}{d_{\mathrm{v}}} \frac{f_{\mathrm{y}}}{E_{\mathrm{s}}} \,.\, \left(\frac{m_E}{m_R}\right)^{1{,}5} \tag{11}$$

The equation for k_ψ is specified according to the failure criterion suggested by Muttoni, Ruiz [9] to obtain a more accurate value.

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Tab. 3 Results of analytical calculations of punching shear slabs.

			Eurocode 2		Second generation of Eurocode 2		Model code 2010	
		V_{exp} kN	V_{EC2} kN	V_{exp} / V_{EC2}	V_{prEC2} kN	V_{exp} / V_{prEC2}	V_{MC10} kN	V_{exp} / V_{MC10}
S. Leelatanon 0.8	**0**	*180*	*124.9*	*1.44*	*159.1*	*1.13*	*152.0*	*1.18*
	50	*159.8*	*120.0*	*1.33*	*145.3*	*1.10*	*145.7*	*1.10*
	100	*150.4*	*117.9*	*1.28*	*135.0*	*1.11*	*143.6*	*1.05*
S. Leelatanon 1.5	**0**	*260.9*	*157.0*	*1.66*	*200.1*	*1.30*	*195.1*	*1.34*
	50	*217.8*	*149.6*	*1.46*	*181.2*	*1.20*	*184.2*	*1.18*
	100	*217.5*	*145.2*	*1.50*	*166.2*	*1.31*	*177.4*	*1.23*
S. Sahoo N	**0**	*207.3*	*135.6*	*1.53*	*172.0*	*1.21*	*168.1*	*1.23*
	50	*214.2*	*133.5*	*1.60*	*159.4*	*1.34*	*165.3*	*1.30*
	100	*224.4*	*135.0*	*1.66*	*150.7*	*1.49*	*167.3*	*1.34*
S. Sahoo M	**0**	*254.7*	*154.1*	*1.65*	*195.4*	*1.30*	*192.8*	*1.32*
	50	*254.2*	*153.8*	*1.65*	*183.5*	*1.39*	*192.3*	*1.32*
	100	*258.6*	*153.3*	*1.69*	*170.5*	*1.52*	*191.5*	*1.35*
S. Sahoo H	**0**	*258.1*	*172.4*	*1.50*	*216.2*	*1.19*	*215.2*	*1.20*
	50	*260.0*	*168.2*	*1.55*	*201.2*	*1.29*	*210.2*	*1.24*
	100	*267.0*	*169.9*	*1.57*	*190.5*	*1.40*	*212.7*	*1.26*
J. Xiao	**0**	*320.0*	*268.0*	*1.19*	*349.0*	*0.92*	*332.4*	*0.96*
	50	*307.1*	*257.8*	*1.19*	*313.8*	*0.98*	*319.2*	*0.96*
	100	*303.4*	*235.3*	*1.29*	*266.6*	*1.14*	*290.6*	*1.04*
L. Francesconi	**0**	*68.7*	*53.3*	*1.29*	*63.6*	*1.08*	*56.0*	*1.23*
	50	*66.2*	*51.0*	*1.30*	*61.6*	*1.07*	*54.7*	*1.21*
	100	*70.0*	*47.7*	*1.47*	*55.6*	*1.26*	*51.7*	*1.35*
Z. I. Mahmoud 12.5	**0**	*157.5*	*111.8*	*1.41*	*143.8*	*1.10*	*135.2*	*1.16*
	50	*137.5*	*106.8*	*1.29*	*130.0*	*1.06*	*128.9*	*1.07*
	100	*122.0*	*105.3*	*1.16*	*123.3*	*0.99*	*126.6*	*0.96*
Z. I. Mahmoud 25.0	**0**	*172.5*	*113.9*	*1.51*	*164.1*	*1.05*	*148.8*	*1.16*
	50	*140.5*	*108.8*	*1.29*	*146.2*	*0.96*	*140.9*	*1.00*
	100	*131.0*	*107.9*	*1.21*	*138.0*	*0.95*	*139.8*	*0.94*
N. Reis	**0**	*163.3*	*137.2*	*1.19*	*195.6*	*0.83*	*192.3*	*0.85*
	50	*169.2*	*137.0*	*1.24*	*185.8*	*0.91*	*191.8*	*0.88*
	100	*160.1*	*136.0*	*1.18*	*174.1*	*0.92*	*190.5*	*0.84*
T. Fecko	**0**	---	*855.9*	---	*897.2*	---	*960.2*	---
Mean				*1.41*		*1.15*		*1.14*
Standard Deviation				*0.17*		*0.18*		*0.16*

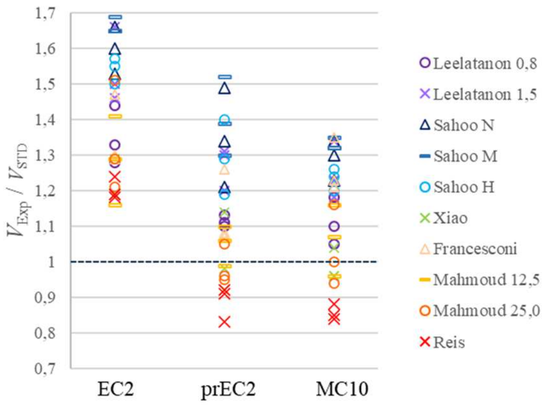

Fig. 4 Punching shear resistance ratios.

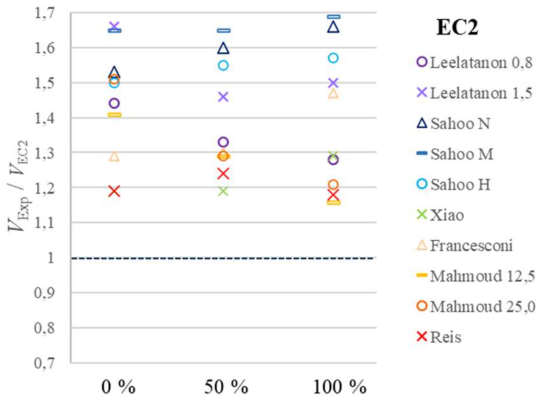

Fig. 5 Punching shear resistance ratios in 3 replacement levels according to EC2.

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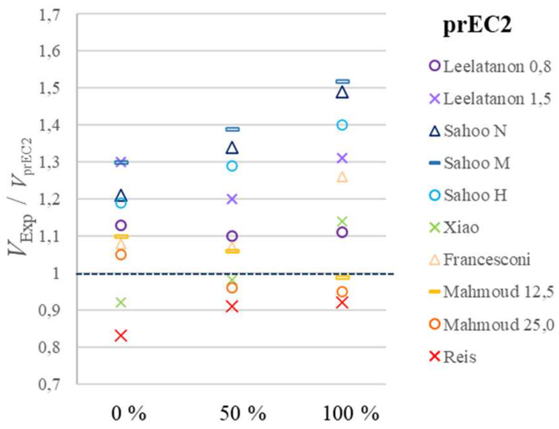

Fig. 6 Punching shear resistance ratios in 3 replacement levels according to prEC2.

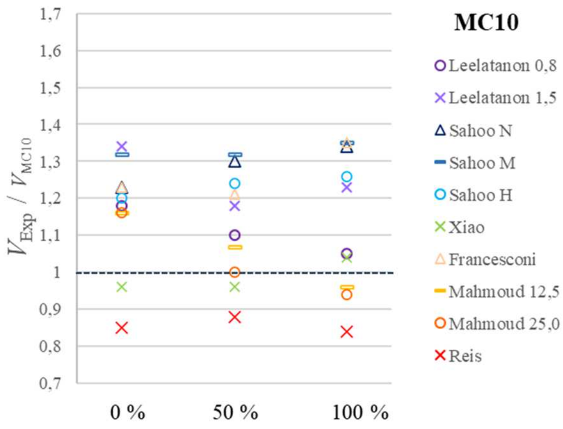

Fig. 7 Punching shear resistance ratios in 3 replacement levels according to MC10.

3 DISCUSSION

The analyses show that the current codes of practice are able to predict punching shear capacity with a quite high accuracy even for flat slabs cast from RAC. Eurocode 2, which we have used in the past decade, shows very safe results (even with 0% replacement of aggregate). The reason is the small thickness of the specimens (size effect), which is not covered by the EC2 model for effective depths lower than 200 mm.

It will be interesting to observe the behavior of the RAC slabs with the thickness of a real structure proposed in the experiment presented in section 5. The effective depth d is 204 mm, which allows us to take into account the size effect k_h < 2.0. I expect that the experimental results will be much closer to the results of analytical calculations compared to the other research works.

4 CONCLUSION

According to Tab. 3 and the graphs in Fig. 4–7, we can see the following conclusion:

- The most conservative design code seems to be Eurocode 2, and the punching shear capacity ratios V_{exp} / V_{EC2} are in the range of 1.18 to 1.69 with a mean value of 1.41.
- Model code 2010 and the second generation of Eurocode 2 are more accurate with regard to the results of the experiments: the mean values of the V_{exp} / V_{calc} ratio are 1.14 and 1.15, and CoV was 0.16 and 0.18.

To summarize, engineers have to expect a lower compressive strength of concrete due to the replacement of CNA in concrete with CRA. However, there is no significant difference between any levels of CNA replacement in the results for punching shear capacity ratios. Besides the decrease in punching shear capacity due to the lower strength of concrete, there is no proof of any significant drop in the shear capacity of the slab caused by the presence of CRA.

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