ASSESSMENT OF DEFLECTION OF REINFORCED BEAMS MADE OF RECYCLED AGGREGATE CONCRETE SUBJECTED TO FLEXURAL LOAD

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Abstract

This article deals with assessing and comparing deflection and numerical analysis of reinforced concrete beams. The objective is to verify the use of recycled aggregate concrete in structural elements subjected to bending and compare them to identical beams with natural aggregate incorporated.

The experiment proved that the reliability factor decreased negligibly. The parametric study confirmed similar deflection values during the experimental process and partially explained the studied parameters.

Keywords

Recycled aggregate concrete, reinforced beam, flexural load

1 INTRODUCTION

Construction and waste management depends on the standards and laws in a given country [1]. Current legislation is sceptical about using recycled aggregates in load-bearing structures in larger volumes due to the heterogeneity of such aggregates [2] and their generally lower quality than natural aggregates [3]. Under these conditions, ensuring the required quality and uniformity of processes is extremely important from a safety point of view. Quality commitment schemes must establish standard rules for producers and suppliers to increase confidence in recycled aggregates and promote their use in practice.

The mechanical parameters of this modified material are different in comparison to the concrete with natural aggregate. The compressive strength of recycled aggregate concrete is generally lower than that of traditional mixes. The trend is decreasing when the coarse aggregate substitution ratio increases ([4], [5], [6], [7], [8]). However, the extent of this decrease mainly depends on the substitution ratio, concrete production method [9] and the type of aggregate, size and origin [10].

Since recycled aggregates are composed of concrete waste (whose adhered mortar has a lower Young’s modulus than the original aggregate) and other constituents that are less stiff than stone (e.g. most ceramics), Young’s modulus of concrete decreases when recycled aggregates are used. Moreover, recycled aggregate concrete has additional interfacial transition zones in comparison to conventional concrete, and this results in a larger overall volume of the interfacial transition zone (which is the most deformable mesoscopic phase of concrete [11] and additional cracks also decrease Young’s modulus [12].

This article deals with the comparison of beams with identical dimensions and reinforcement. Beams made from 100% recycled aggregate are compared with a beam made from traditional natural aggregate. The different deformation and strength properties of the concrete indicate different failure and deflection values. The paper also includes a parametric study, which was executed in the ATENA computational program and attempts to calibrate the model for subsequent experiments and analyses. The actual resistance is compared with the predicted resistance and with the resistance that the beams should have if compared with the mechanical values of standard concrete.

2 EXPERIMENT

The experimental part dealt with the flexural stresses of concrete beams made of recycled aggregate. The beams were reinforced with B500 B steel reinforcement and included longitudinal and shear reinforcement. The cross-section was rectangular with dimensions of 150 mm × 350 mm. The length of the beam is 4000 mm. The cover of the stirrups is 20 mm. The beams were constructed in three types of mixes: a plain concrete mix designated as

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reference – REF, a recycled aggregate mix derived mainly from brick rubble abbreviated as REB and a recycled aggregate mix derived mainly from concrete structures denoted as REC. The beams were manufactured by ERC-tech s.r.o. and tested in the laboratories of TZÚS Brno.

Beams

Three beams were tested for flexural stresses, one from each mix (REF, REB, REC). The dimensions and schematic representation of the assembly are illustrated in **Chyba! Nenalezen zdroj odkazů.**. During the test, the applied force was measured by the pressure in the hydraulic press and the actual deflection at the load point and mid-span was measured. The crack development and crack width were also recorded. The beam was loaded with a force increment where one step was 2.5 kN, for each point of force (P). **Chyba! Nenalezen zdroj odkazů.** shows the load test progress for all mix types. The deflection is compared at mid-span. The type of failure was flexural – crushing the concrete in the compressed area.

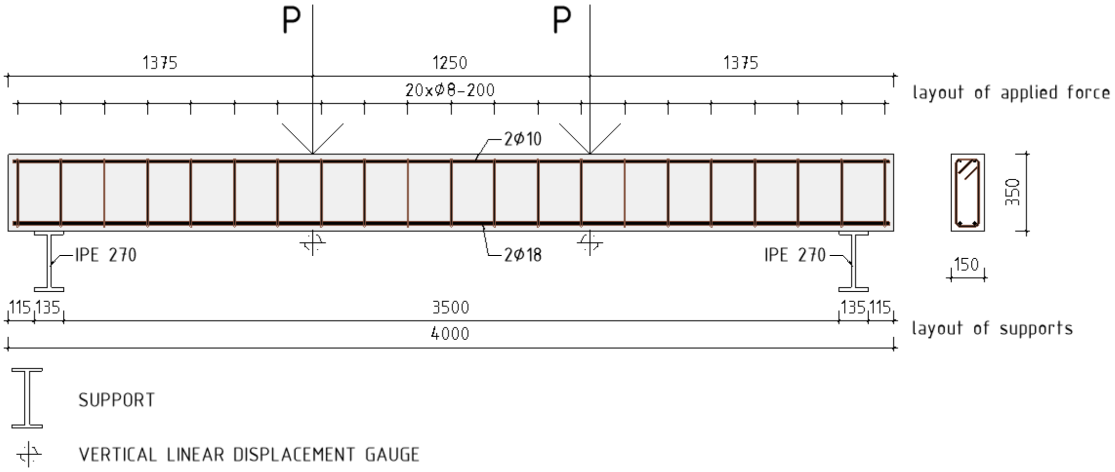

Fig. 1 Load test arrangement.

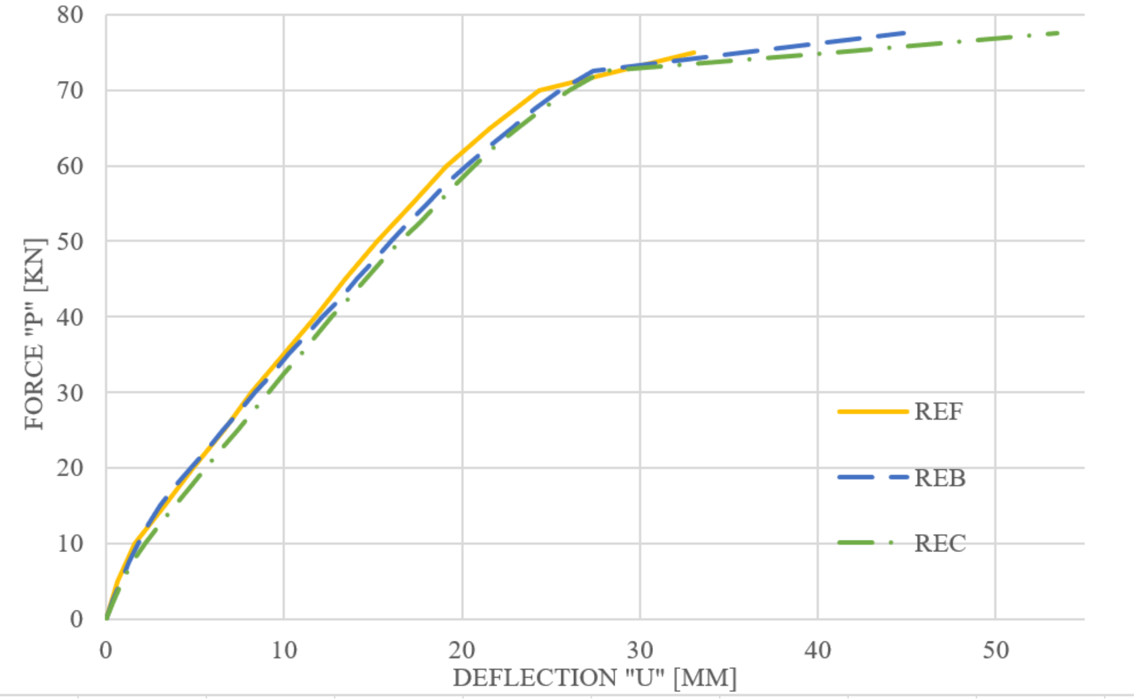

Fig. 2 Results for tested mixtures.

Concrete samples

The experiment also includes testing ~~of~~ concrete samples. Three cubes and three prisms were cast from the REC and REB mixes, and two cubes were cast from the reference mix REF. All compounds were considered to have concrete strength class C25/30. The compressive strengths for the cube and prism, and the compressive modulus of elasticity of the concrete were obtained from the tests. The results for the respective mixes are shown in Tab. 1 – Tab. 3. Tab. 4 shows the ratio of the prism and cube strengths for the individual compounds. The reinforcement parameters considered are those given by the manufacturer (mean values). These values are shown in Tab. 5.

Tab. 1 Mechanical parameters of REF concrete.

Label	ρ [kg.m^{-3}]	$f_{c,cube}$ [MPa]	$f_{c,prism}$ [MPa]	E_c [MPa]
REF1	*2260*	*37.0*	-	-
REF2	*2260*	*38.5*	-	-
Mean	*2260*	*37.8*	-	*31500*

Tab. 2 Mechanical parameters of REB concrete.

Label	ρ [kg.m^{-3}]	$f_{c,cube}$ [MPa]	$f_{c,prism}$ [MPa]	E_c [MPa]
REB1	*1840*	*40.4*	*26.9*	*12600*
REB2	*1910*	*46.7*	*25.9*	*13200*
REB3	*1870*	*39.4*	*26.9*	*12800*
Mean	*1870*	*42.2*	*26.6*	*12900*

Tab. 3 Mechanical parameters of REC concrete.

Label	ρ [kg.m^{-3}]	$f_{c,cube}$ [Mpa]	$f_{c,prism}$ [Mpa]	E_c [Mpa]
REC1	*2020*	*39.0*	*34.2*	*18700*
REC2	*2030*	*41.0*	*34.0*	*19300*
REC3	*2030*	*40.1*	*33.1*	*17800*
Mean	*2030*	*40.0*	*33.8*	*18600*

Where ρ is the volumetric weight, $f_{c,cube}$ is the cubic compressive strength, $f_{c,prism}$ is the prismatic compressive strength and E_c is the modulus of elasticity of concrete.

Tab. 4 Ratio of prismatic and cubic compressive strength for mixtures.

Type of mixture	$f_{c,prism} / f_{c,cube}$
REB	*0.63*
REC	*0.85*

Tab. 5 Mechanical parameters of steel reinforcement.

E_s (MPa)	f_y (MPa)
200000	*550*

Where E_s is the modulus of elasticity of reinforcement steel and f_y is the yield strength of reinforcement steel.

3 NONLINEAR FINITE ELEMENT MODEL

A nonlinear finite element model (NLFEM) of the tested beams was developed for comparison with the experiment. The material-concrete parameters, namely "Aggregate size" and "Fixed crack model coefficient", were varied, which should influence the simulation progress, crack formation, resulting deflection and overall load capacity. In order to save time, half of the beam was modelled. This was possible due to ~~the~~ symmetrical loading. "Aggregate size" describes the diameter of the largest aggregate grain used, directly influencing the dowel effect. Values of 8 mm, 16 mm and 24 mm were selected. In the charts, this parameter is described as "P2". "Fixed crack model coefficient" describes the crack propagation. This parameter is directly linked to the fracture energy.

At a value of 0, the crack completely rotates and adapts to the main stress directions. At a value of 1, it is completely fixed, which means that the crack orientation is fixed at the beginning and does not change during the simulation. After a preliminary analysis, I decided to choose values of 1.0, 0.99, 0.98, and 0.97. In the graphs, this parameter is denoted as "P1". **Chyba! Nenalezen zdroj odkazů.** 3 illustrates the beam model in ATENA.

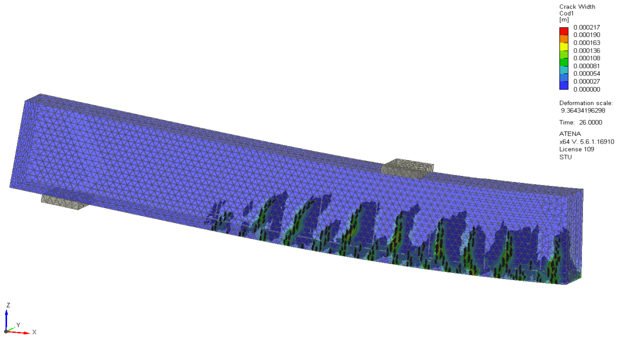

Fig. 3 Deformed NLFEM model of the beam.

4 RESULTS

Tab. 6 shows the predicted resistances according to the mechanical parameters obtained from the possible material tests displayed in Tab. 1, Tab. 2 and Tab. 3. The parameters which were not obtained by tests were taken from the Eurocode standard for concrete class C25/30 according to Eurocode 2 (2004). Flexural resistance was calculated by the standard design procedure using the parabola-rectangle diagram for concrete under compression. The actual resistance value was achieved in the experiment. Tab. 7 shows the ratio between the measured resistance and the theoretical resistance according to the values obtained from the material tests and according to the standard values of the strengths attributed to concrete class C25/30.

Tab. 6 Values of predicted and tested flexural resistances.

Mixture	$M_{\mathrm{R,test}}$ **[kNm]**	$M_{\mathrm{R\ C25/30}}$ **[kNm]**	$M_{Experiment}$ **[kNm]**
REF	*78.7*	*76.9*	*89.4*
REB	*79.7*	*76.9*	*88.3*
REC	*77.7*	*76.9*	*89.4*

Where $M_{\mathrm{R,test}}$ is the predicted flexural resistance with tested mechanical parameters, $M_{\mathrm{R\ C25/30}}$ is the predicted flexural resistance with standardised mechanical parameters and $M_{Experiment}$ is the tested flexural resistance.

Tab. 7 Ratios of teste~~s~~d and predicted flexural resistances.

Mixture	$M_{Experiment}$ / $M_{\mathrm{R\ test}}$	$M_{Experiment}$ / $M_{\mathrm{R\ C25/30}}$
REF	*1.1*	*1.2*
REB	*1.1*	*1.1*
REC	*1.2*	*1.2*

Tab. 8 shows the comparison of the measured and predicted deflection..It also includes the ratio of these values, which indicates how much the predicted deflection is less or greater than the actual measured deflection. 80% was chosen to compare the performance of all mixes at the same value close to the failure in the plastic zone.

Tab. 8 Comparison of measured and predicted mid-span deflection.

Mixture	$U_{\mathrm{experiment}}$ **[mm]**	U_{model} **[mm]**	$U_{\mathrm{experiment}}$ / U_{model}
REF	*19.11*	*16.66*	*1.15*
REB	*20.21*	*19.63*	*1.03*
REC	*20.68*	*17.47*	*1.18*

Where $U_{\mathrm{experiment}}$ is the tested deflection and U_{model} is the predicted deflection according to the model.

The parametric study compared all three mixtures. **Chyba! Nenalezen zdroj odkazů.** shows the simulation runs for the REB mixture. The simulation with a 24 mm aggregate grain and a P1 = 0.98 coefficient replicated the experiment most ideally. The appearance of the first flexural cracks occurred later, and the measured deflection at 80% load is 3% larger than predicted. **Chyba! Nenalezen zdroj odkazů.** corresponds to the simulations for the REC mix. The simulation with an aggregate grain of 8 mm and a P1 = 0.99 coefficient reproduced the experiment most ideally. The appearance of the first flexural cracks occurred later, and the measured deflection at 80% load is 18% larger than predicted. The last **Chyba! Nenalezen zdroj odkazů.** shows the simulation for the REF mixture. The simulation with an aggregate grain of 16 mm and a P1 = 0.99 coefficient replicated the experiment most ideally. The appearance of the first flexural cracks occurred later, and the measured deflection at 80% load is 15% larger than predicted. **Chyba! Nenalezen zdroj odkazů.** shows the simulations with P1 = 0.99 and a variable aggregate grain for the REB mix. In contrast, Fig. 8 shows simulations with a parameter P2 = 16 mm and with a variable P1 for the REB mix.

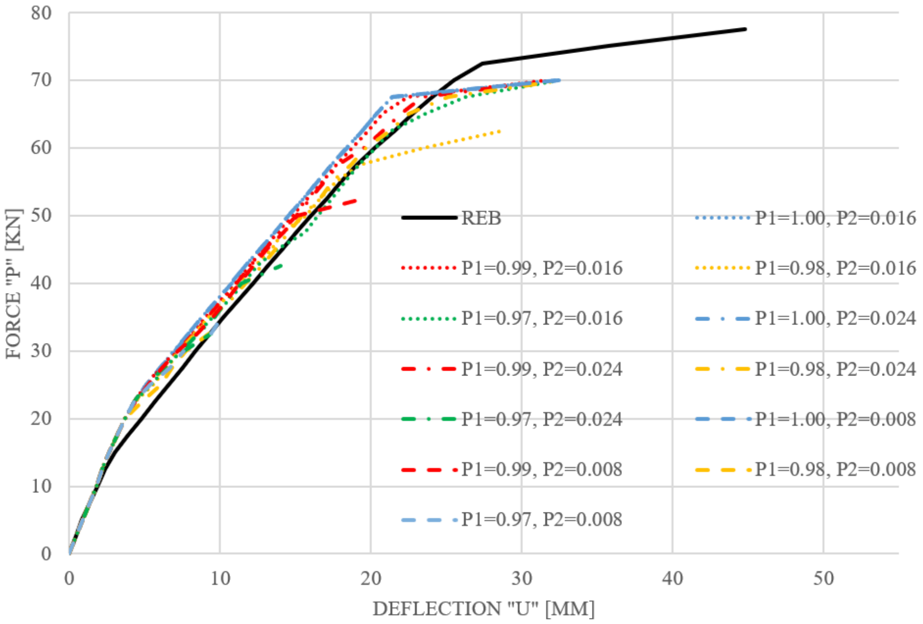

Fig. 4 All parameter simulations for the REB mixture.

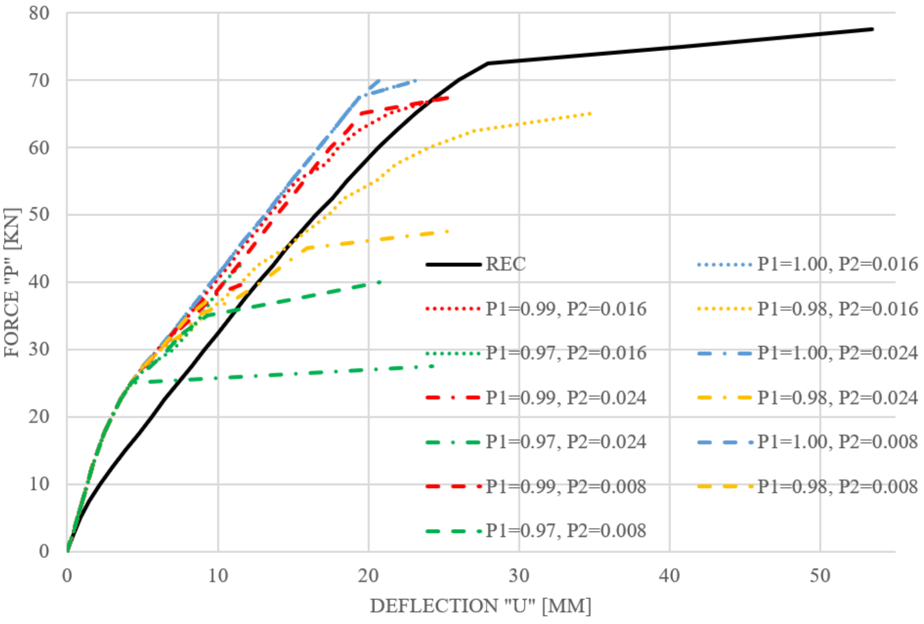

Fig. 5 All parameter simulations for the REC mixture.

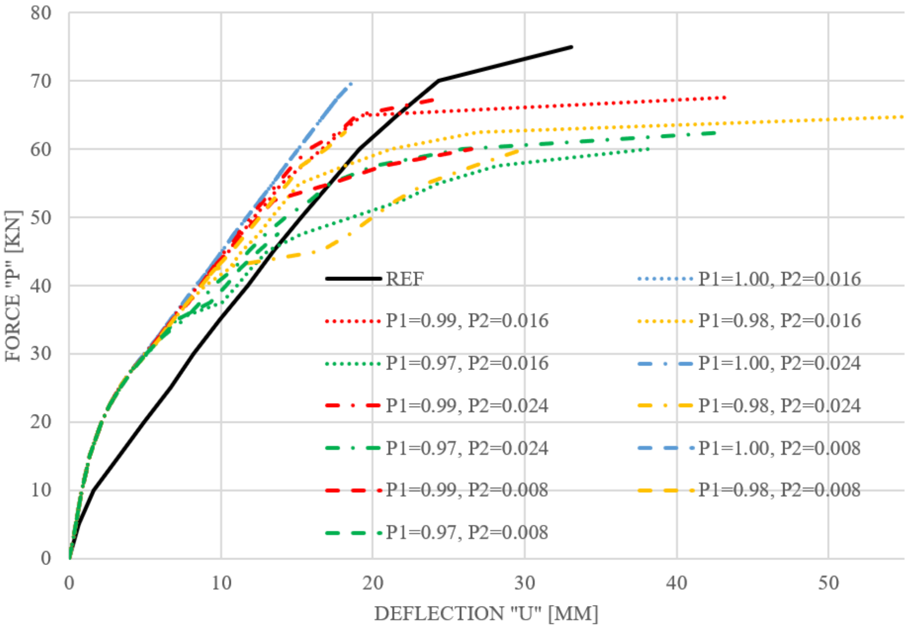

Fig. 6 All parameter simulations for the REF mixture.

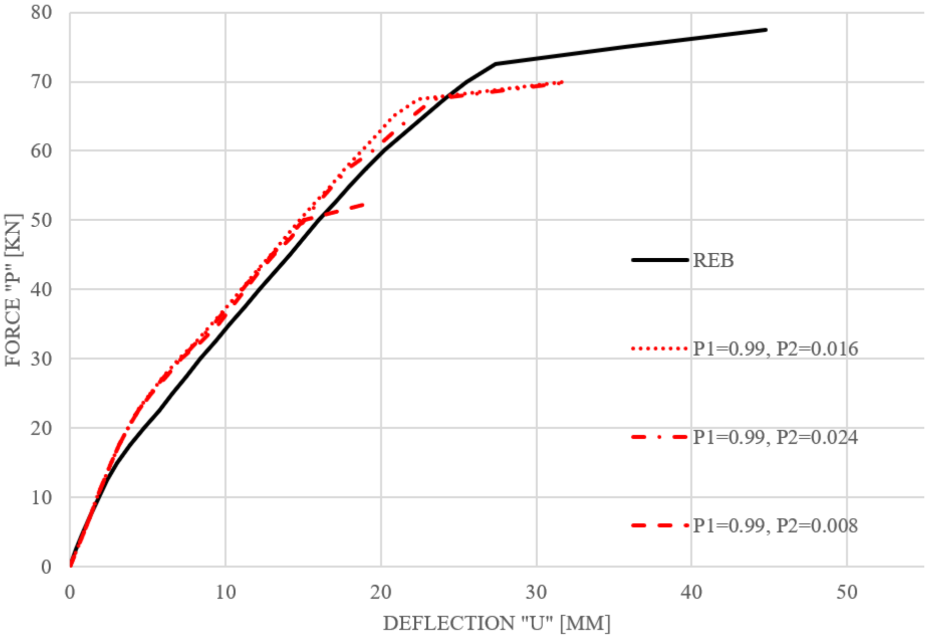

Fig. 7 Selected combinations of parameters for the REB mixture.

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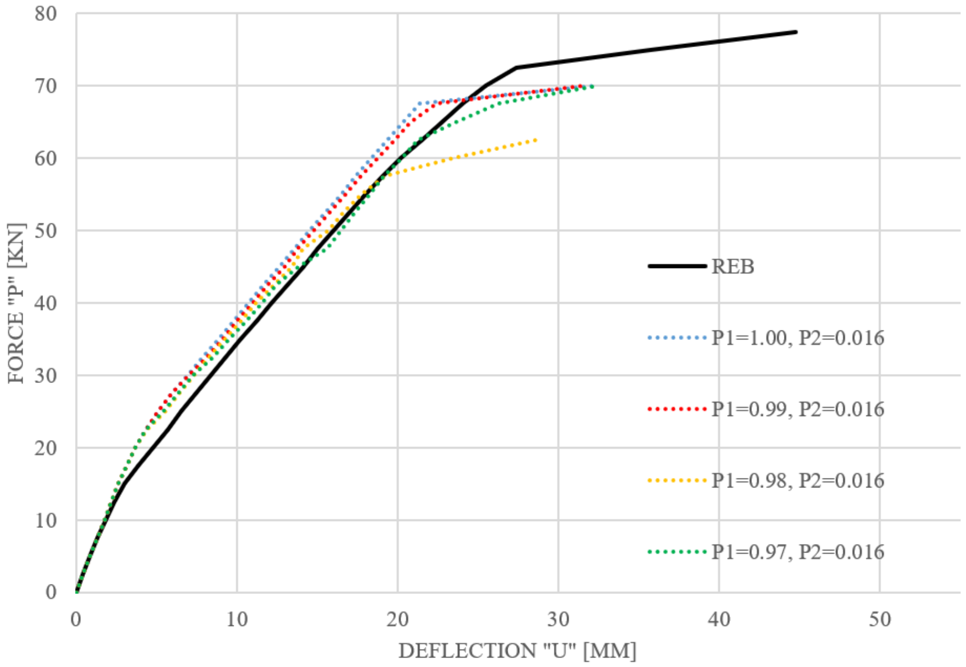

Fig. 8 Selected combinations of parameters for the REB mixture.

5 DISCUSSION

The different values of the modulus of elasticity for the different mixtures affected the overall load capacity and deflection only to a minor extent. Although the beams made from the recycled mixes had higher strength characteristics, the difference in load capacity was minimal. The difference in deflections for individual mixtures is insignificant despite the diametrically different values of the modulus of elasticity of concrete.

The initial stiffness of all mixes is lower than predicted and first cracks occur sooner than expected. After the formation of cracks, the predicted stiffness resembles the real stiffness.

According to the parametric study, the appropriate values of the parameter "P1" - fixed crack coefficient are 0.98 and 0.99. A value of 1 also provided relatively accurate data, while a value of 0.97 was the least appropriate. The value of "P2" – Aggregate size had ~~a~~ more significant and less interpretable variance. A different value was suitable for each mixture, more detailed study of this parameter is planned.

6 CONCLUSION

- The differences in deflection for each mixture are negligible. The parametric study assumed that approximately similar deflection values for all mixtures.
- The actual element resistances were more significant than predicted in all cases~~,~~: 14%, 11% and 15% for REF, REB and REC, respectively. If the resulting resistances were compared with the standard values of C25/30 concrete, which was the target strength of the concrete, these values would increase even further.
- The different cube and prism strength ratios for the recycled mixes confirm the problematic heterogeneity of recycled aggregate concretes.
- Further and more detailed parametric study is needed. The parameter describing the aggregate size has not yet provided a sufficient conclusion. There are definitely more parameters which will affect the overall performance of the element, for example, the stress-strain relation, fracture energy, tensile strength, detailed shrinkage and creep effects.

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