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Influence of recycled concrete aggregate content on load-bearing capacity and deformability of reinforced concrete slabs under static loading

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ABSTRACT

This paper presents the results of an experimental study on the effect of progressive replacement of natural aggregate with recycled concrete aggregate (RCA) on bearing capacity, deformability and crack development in reinforced concrete slabs subjected to emergency loading. The study included four series of slabs in which the proportion of RCA was 0%, 20%, 50% and 100% by weight to natural coarse aggregate, respectively. The specimens were made with CEM I 42.5 R cement and the concrete mixtures had a constant w/c ratio 0.51. Measurements of ultimate bearing capacity, deflections, crack development and regression analysis of the force-deflection relationship were carried out. The results showed that replacing the natural aggregate with RCA to a level of 20% did not result in a significant decrease in bearing capacity or excessive deflections. In contrast, increasing the proportion of RCA to 50% and 100% led to a systematic reduction in load carrying capacity (by 6.4% and 12.5%, respectively) and an increase in the deformability of the elements, especially in the final loading phases. More intensive crack development was also found at higher RCA contents, which is related to the lower stiffness and higher porosity of the recycled concrete. The results obtained indicate that concrete with RCA can be used in structural elements provided that the proportion of secondary aggregate is controlled and that the technology for producing this type of concrete is further improved.

Keywords: recycled concrete, recycled concrete aggregate, bearing capacity, deflections, reinforced concrete slabs, cracking, regression analysis

INTRODUCTION

In recent years, there has been a rapid expansion of construction and an intensification of demolition work, leading to a systematic increase in the amount of construction and demolition waste generated. This waste represents a serious burden on the environment [1]. At the same time, natural aggregate resources are gradually being depleted and their extraction is associated with environmental degradation and high costs [2]. One way to reduce the consumption of primary raw materials is to reuse concrete waste as aggregates (RCA) in new concrete mixtures. Concrete recycling reduces landfill waste, the CO_2 emissions associated with the production and transport of natural aggregates, and material costs [3, 4]. Recent studies emphasize that the application of recycled aggregates in concrete not only contributes to environmental sustainability but also aligns with circular economy principles in construction, promoting material efficiency and reducing dependency on virgin resources [5].

Research into the use of RCA in structural concrete has been conducted intensively since the 1990s [5, 6]. The utilization of RCA is encumbered by several challenges and difficulties, which serve to limit its widespread use. One such factor is the presence of impurities in the recycled aggregate, which, by extension, is also present in the concrete. This has been shown to result in a reduction in compressive strength. Furthermore, technological difficulties are also associated with the production of a mix with RCA, including a decrease in workability or an accelerated setting time during placement. Furthermore, concrete incorporating secondary aggregates has been observed to demonstrate a decline in additional parameters, including the modulus of elasticity and the adhesion of aggregate to mortar [7]. It is evident that properties which have a detrimental effect on the durability of concrete, such as abrasion resistance, shrinkage, carbonation, water permeability, as well as resistance to chlorides, sulphates, alkalis and to freeze-thaw cycles, also lead to deterioration [8].

Nevertheless, these unfavorable characteristics of concretes with recycled aggregates can be significantly mitigated by developing mixes with low w/c ratios and by replacing the fine fractions of secondary aggregates with high-quality natural sands. It is evident that the utilization of aggregates that have undergone appropriate improvement processes, such as thermo-mechanical treatment, mechanical abrasion, screw milling or gravity concentration, results in a substantial enhancement in the quality of concretes composed of secondary aggregates [9].

The findings of research conducted about concrete mix technology indicate that a significant enhancement in the workability of concrete with secondary aggregates can be achieved by ensuring appropriate dosage and the correct sequence of mixing of the ingredients. In lieu of the customary simultaneous amalgamation of all ingredients, it is advised that the coarse aggregate be initially blended with a modest quantity of water. Thereafter, the fine aggregate should be amalgamated with an additional portion of water. Subsequently, the cement and other binding agents should be introduced, along with the final portion of water [10].

Xiao et al. (2012) posited that the primary issue associated with the utilization of RCA is the presence of residual cement mortar on the surface of the secondary aggregate. This results in increased porosity and inhomogeneity of the concrete structure, which ultimately leads to a reduction in its mechanical strength and durability compared to concrete on natural aggregate. The researchers demonstrated that the most significant disparities are evident when natural aggregate is entirely substituted by RCA. Conversely, at lower replacement levels (ranging from 25 to 30%), the mechanical properties of the concrete remain at an acceptable level for structural applications [3].

To date, a significant proportion of research has been dedicated to investigating the general properties of concrete, including compressive strength, water absorption and frost resistance [11, 12]. However, comparatively little attention has been paid to the behaviors of structural elements such as concrete slabs, particularly in the context of real, ad hoc loading conditions. Given that slabs frequently function under concentrated loads [e.g. industrial floors, foundations, ceilings], it is imperative to examine their behavior under such conditions. In order to achieve full acceptance of recycled concrete for large-scale structural applications, detailed and reproducible tests are required to confirm its reliability. In the case of structural elements, it is imperative to assess both load-bearing capacity and deflections, which affect the safety of use, comfort and durability of the structure.

Schubert et al. (2012) conducted a study to ascertain the shear capacity of reinforced concrete slabs that were not reinforced with transverse reinforcement and were composed of RCA-based concrete and brick aggregate. It was demonstrated that slabs incorporating RCA (reactive concrete admixture) achieve shear strengths that are comparable to those of slabs comprising natural aggregate. However, it was observed that an augmentation in the brick aggregate content resulted in a substantial decline in bearing capacity. This phenomenon was ascribed to a diminished interlock mechanism of the aggregate grains and a reduction in the stiffness of the concrete [13].

In contrast, Michaud et al. (2016) conducted a study that focused on the analysis of deformability and crack development in reinforced concrete slabs made of concrete containing up to 30% RCA. Utilizing contemporary measurement techniques, including digital image correlation and fiber-optic strain sensors, the authors demonstrated that slabs containing RCA may exhibit earlier crack initiation and slightly higher crack dilation. However, their overall shear capacity does not differ significantly from that of conventional concrete slabs [1].

In a study undertaken by Imjai et al. (2023), natural aggregate was substituted with 100% RCA in reinforced concrete slabs that had been reinforced with FRP composite bars. Research findings demonstrated that even complete replacement of natural aggregate resulted in elements that satisfied serviceability requirements. However, an elevated propensity for shear deformation following diagonal cracking was observed [14, 15].

Furthermore, Kefyalew et al. (2023) conducted experimental investigations on composite slabs, analyzing the effects of full and partial replacement of natural aggregate on flexural bearing capacity, long-term deflections and dynamic behavior. The findings of the study demonstrated that, even with 100% replacement of the RCA, the reduction in bearing capacity did not exceed a few percentage points in comparison with the reference concrete. Concurrently, the remaining performance parameters remained within acceptable limits [2].

Recent research also explores hybrid solutions. Al-Sudani et al. (2024) introduced a double-profile steel sheet dry board (DPSSDB) system filled with recycled concrete, achieving up to 170% increased bending capacity relative to traditional slabs, even with up to 50% replacement of aggregates using lightweight recycled materials [16]. Ganjeena et al. (2024) further confirmed that porcelain waste and RCA can enhance permeability and sustainability in pervious concrete, although mechanical strength declines with high substitution rates [17].

The extant research demonstrates that concrete incorporating recycled aggregate has potential for structural applications [18]. Large-scale structural applications of recycled concrete should be accepted; detailed and reproducible tests are required to confirm its reliability. In the case of structural elements, it is imperative to assess both load-bearing capacity and deflections, which affect the safety of use, comfort and durability of the structure. A significant proportion of extant studies are predicated on extreme scenarios (0% or 100% recycled aggregate). Studies on mixtures with partial replacement (e.g. 20%, 50%) allow the development of optimal formulations that combine environmental benefits with the required performance.

In view of the factors that have been considered, the objective of the present study was to conduct experimental research to evaluate the effect of utilizing recycled concrete aggregate on the load-bearing capacity and deformability of concrete slabs subjected to ad hoc loading.

MATERIALS AND METHODS

Materials

Cement

The concrete mixtures were prepared using Portland cement CEM I 42.5 R supplied by CEMEX. The detailed physical and chemical properties of the cement are presented in Table 1.

According to the classification CEM I 42.5 R, it is characterized by high early strength, with 28-day compressive strength within 42.5–62.5 MPa.

Aggregates

Natural aggregates included fine fractions of 0–2 mm and 2–4 mm, as well as coarse aggregate fraction of 4–8 mm. The natural aggregates featured rounded, spherical shapes with smooth edges. Prior to use, the aggregates were sieved and fractionated.

Table 1. Physical and chemical properties of CEM I 42.5 R cement

Property	Unit	Mean value	Standard requirement [PN-EN 197-1:2012][19]
Initial setting time	min	140	≥ 60
Final setting time	min	181	—
Water demand	%	27.1	—
Volume stability	mm	0.9	≤ 10
Specific surface area	cm^2/g	3938	—
Compressive strength (2 days)	MPa	25.0	≥ 20
Compressive strength (28 days)	MPa	60.0	≥ 42.5 ≤ 62.5
SO_3 content	%	2.62	≤ 4
Cl^- content	%	0.043	≤ 0.10
Insoluble residue	%	0.32	≤ 5
Loss on ignition	%	1.59	≤ 5

Recycled coarse aggregate with a particle size of 4–8 mm was obtained through mechanical crushing of concrete debris using a laboratory jaw crusher LAB-02-130, enabling precise control of grain size distribution. The crushed material was further sieved using a laboratory shaker LPzE-4e operating at 50 Hz with vertical-torsional vibrations to obtain the target 4–8 mm fraction (Figure 1).

The recycled aggregate replaced 20%, 50%, or 100% of the natural coarse aggregate fraction [4–8 mm] in respective mixtures.

Mixing water

Potable water meeting the requirements of PN-EN 1008 was used for mixing concrete. The water was clear, colorless, and free of impurities [20].

Concrete mix proportions

The mix compositions of the tested concretes are summarized in Table 2.

Reinforcement

The reinforcement consisted of welded meshes made of B500SP steel bars with a diameter of ϕ8 mm, spaced at 120 × 120 mm, in accordance with applicable standards. The reinforcement scheme is illustrated in Figure 2.

Testing procedure

The experimental program was designed to assess the influence of recycled coarse aggregate replacement on the mechanical behavior of reinforced concrete slabs subjected to short-term loading. The study was conducted in two stages:

Stage 1: Mechanical properties of concrete were assessed through compressive strength tests on cubic [100 × 100 × 100 mm] and cylindrical (ϕ150 × 300 mm) specimens. The tests were performed according to PN-EN 12390-1, PN-EN 12390-2, PN-EN 12390-3, and PN-EN 12390-5 standards [21–24]. Stage 2: Full-scale tests on rectangular reinforced concrete slabs were carried out for four series:

Figure 1. Secondary aggregate fraction 4–8 mm

- N – slabs made entirely with natural aggregates,
- RC20 – slabs with 20% replacement of coarse natural aggregate with recycled aggregate,
- RC50 – 50% replacement,
- RC100 – 100% replacement.

The slabs had dimensions of 600 × 1200 × 80 mm. The test setup included measurement of mid-span deflections, observation of crack initiation and propagation, and determination of ultimate failure loads (Figure 3).

The test continued until failure, defined as concrete crushing in the compression zone or excessive crack width accompanied by a reduction in load-carrying capacity. The maximum load recorded at failure was considered as the ultimate flexural strength. For the compressive strength tests of concrete specimens, six cube samples (10×10×10 cm) were prepared for each concrete type. For the experimental elements (slabs), three

Table 2. Concrete mix proportions

Concentrate mix type	Cement CEM I 42.5 R [kg/m³]	Coarse aggregate – recycled concrete rubble [kg/m³]	Natural coarse aggregate [4–8 mm] [kg/m³]	Natural coarse aggregate [2–4 mm] [kg/m³]	Fine aggregate [0–2 mm] [kg/m³]	Water [l/m³]	w/c	Bulk density [kg/m³]
N	350	828.1	354.9	-	637	178	0.51	2348
RC20	350	662.48	165.62	354.9	637	178	0.51	2348
RC50	350	414.05	414.05	354.9	637	178	0.51	2348
RC100	350	828.1	354.9	354.9	637	178	0.51	2348

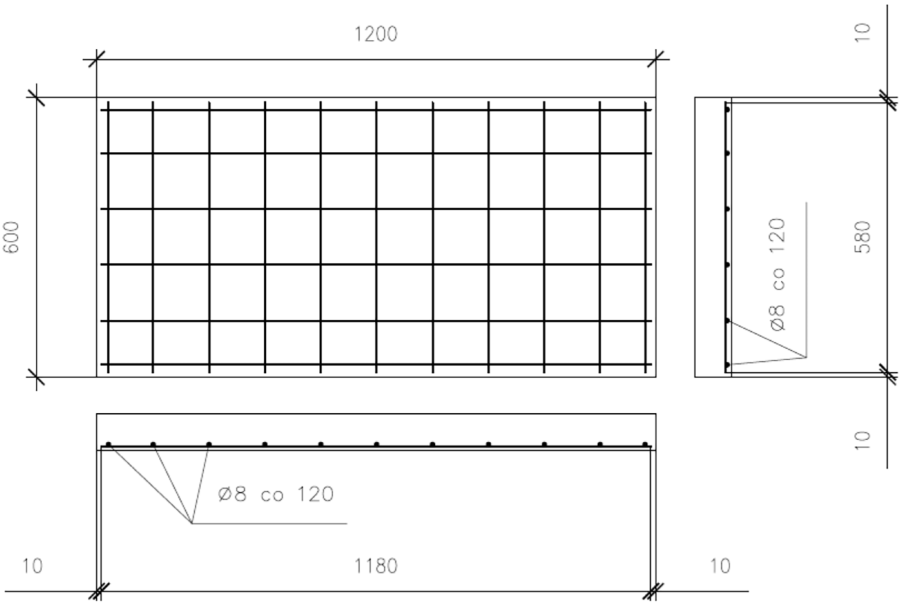

Figure 2. Reinforcement scheme

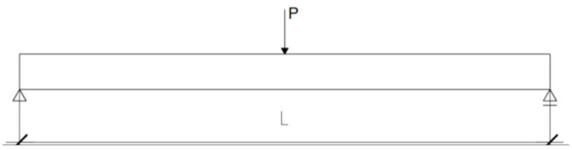

Figure 3. Loading setup of slabs

specimens were prepared for each series. The following average compressive strength values were obtained from the cube specimens:

- for 0% replacement – 37.2 MPa,
- for 20% replacement – 35.2 MPa,
- for 50% replacement – 28.1 MPa,
- for 100% replacement – 22.08 MPa.

Regression analysis

In order to accurately describe the relationship between the loading force and the corresponding deflections of the reinforced concrete slabs, a linear regression analysis was carried out. This analysis enabled a quantitative comparison of the deformability of the slabs as a function of the recycled aggregate content of the concrete mix. For each of the four series studied (N, RC20, RC50 and RC100), a linear regression equation was determined according to the relationship:

$$A = m \cdot F + b \qquad (1)$$

where: a – average deflection of the slab [mm], F – loading force [kN], m – directional regression coefficient [mm/kN], corresponding to the slope of the graph and the inverse of the bending stiffness, b – free expression [mm].

The calculated slope coefficient allows the rate of increase of deflection as a function of applied load to be assessed and thus provides an indirect indicator of the bending stiffness of the test elements. In addition, a coefficient of determination (R^2) was calculated for each series, which indicates the degree of fit of the measured data to the linear model.

A regression analysis was carried out based on all tested deflection values for a given level of applied load, until the ultimate load capacity was reached for each slab. The calculations were performed using Statistica software, applying classical methods for estimating the parameters of the regression model and assuming a significance level of $\alpha = 0.05$.

RESULTS

Plate deflections

The results from the measurements of the average deflections of the slabs for the 3 series [each series containing 3 slabs] are shown in Figure 4.

The results show that replacing up to 20% of the natural aggregate does not significantly reduce the bearing capacity of the slabs. The decrease in bearing capacity of the RCA20 aggregate was only around 1.1%, compared to the

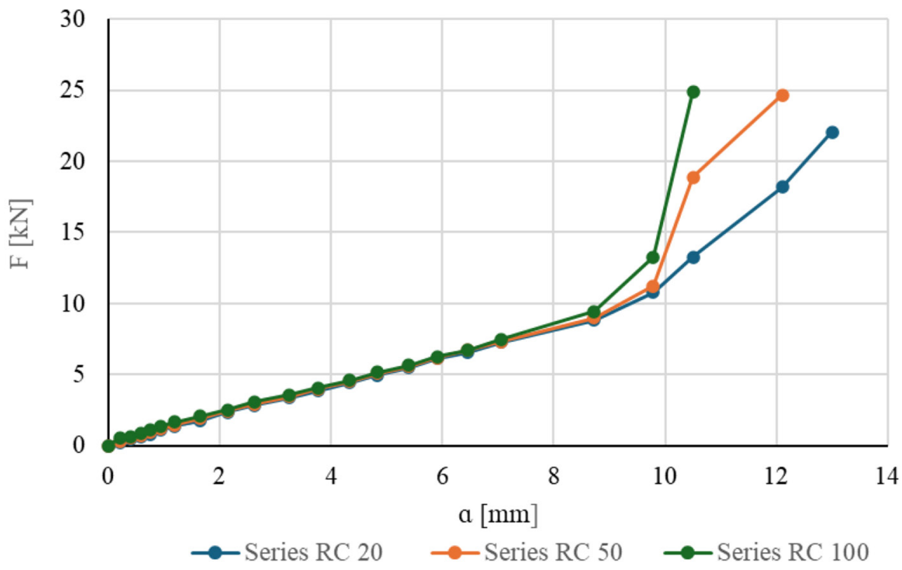

Figure 4. Mean plate deflections of the 3 test series

natural aggregate. Similar findings were reported by Michaud et al. (2016), who demonstrated that the load-bearing properties of elements containing up to 30% substituted natural aggregate remained comparable to those of conventional concrete [1].

Further increasing the proportion of RCA aggregate results in a systematic decrease in bearing capacity: by 6.4 per cent at 50 per cent RCA and by 12.5 per cent at 100 per cent RCA. This decrease can be explained by the deterioration of the microstructure of the contact zone between the aggregate grains and the cement slurry resulting from the presence of old mortar on the secondary aggregate's surface [3, 13].

A study by Imjai et al. (2023), which was conducted on slabs with a high proportion of recycled concrete aggregate, also reported a similar trend of a gradual decrease in bearing capacity with an increase in the proportion of secondary aggregate [13]. The largest increase in deflection was observed in the RC 100 series at higher loading levels. Here, the deformability of the slabs increased significantly, indicating a reduction in stiffness and an increase in susceptibility to excessive deflection when natural aggregate was fully replaced by recycled aggregate.

Table 3. Average breaking forces and maximum deflections for each series

Series	Maximum deflaction a [mm]	Breaking force P [kN]
Seria N	13.00	44.00
Seria RC 20	22.04	43.52
Seria RC 50	24.65	41.20
Seria RC 100	24.89	38.50

Load bearing capacity

The failure strength of each slab was defined as the maximum force at which concrete failure occurred at the point of concentrated force application, accompanied by a significant increase in crack opening and a reduction in force during subsequent loading. The mean failure forces and corresponding maximum deflections for each series are shown in Table 3.

For the reference slabs (N series), the average failure force was 44.00 kN, with a maximum deflection of 13.00 mm. Replacing 20 per cent of the natural aggregate with recycled aggregate (RC 20 series) resulted in a minimum decrease in load capacity of 1.1 per cent (to 43.52 kN), while the maximum deflection increased to 22.04 mm.

As the proportion of recycled aggregates increased, there was a systematic decrease in load-carrying capacity. In the RC 50 series, the breaking force decreased by 6.4% compared to the reference series, dropping to 41.20 kN, with a maximum deflection of 24.65 mm. The greatest reduction in load-carrying capacity was observed in the RC 100 series, where the breaking force was 38.5 kN (a 12.5% decrease) and the deflection reached 24.89 mm.

The results show that replacing up to 20% of natural aggregate with recycled aggregate does not significantly affect the bearing capacity of the slabs. However, a decrease in strength was observed at higher levels of recycled aggregate content, which is consistent with the findings of previous studies by other researchers on the behavior of recycled concrete structural elements [13, 14].

The trend of increased deflections with a higher proportion of CAR is due to the lower modulus of elasticity of recycled concrete. According to studies by Xiao et al. [2012] and Kefyalew et al. (2023), this is directly dependent on the proportion of porous, less stiff old cement slurry on the surface of the CAR grains [3, 2].

Similar relationships were also observed by Michaud et al. (2016), who found that higher deformability and deflection were particularly pronounced when more than 20–30% of the natural aggregate was replaced [1].

Scratch development and failure mechanism

During the tests, the scratching process of the slabs was observed. Up to a load level of around 18 kN, the deflections increased almost linearly with no visible cracking. The first cracks appeared for all series at a load of 18 kN, regardless of the recycled aggregate content. As the load increased, diagonal cracks propagated towards the supports.

A characteristic feature of all the boards tested was the appearance of a bending crack along the shorter edge, running across the width of the slab. While the scratch patterns were similar across all the tested boards, faster crack development and higher crack dilation were observed in the near-failure phase of the components containing a higher proportion of recycled concrete aggregate. This is due to the reduced tensile strength and increased heterogeneity of the recycled concrete [25].

Similar results were obtained by Schubert et al. (2012), who found that cracks developed faster and were more intense in elements made of recycled concrete, particularly in the absence of transverse reinforcement [13].

Results from regression analysis

In the regression analysis, a linear model of the deflection–force relationship was adopted for the entire load range up to the point at which the individual elements failed. Outliers were not explicitly removed from the dataset; however, the regression analysis was limited to the elastic range of 0–10 kN, where the response of the elements remained stable and linear. This approach minimized the influence of potential outliers associated with damage initiation, cracking, or measurement anomalies occurring at higher load levels. Table 4 shows the slope coefficient values and R^2 determination coefficients. Linear regression was used to determine the slope coefficient, which illustrates the rate of deflection increase per unit of applied force. This coefficient is related to the stiffness of the tested elements – the higher the slope coefficient, the lower the stiffness of the slab and the greater its susceptibility to deformation. The regression results confirm a systematic increase in the deformability of the elements as the proportion of recycled aggregate in the concrete mix increases. The results confirm that slabs made of concrete containing recycled concrete aggregate are characterized by greater susceptibility to deflection under increasing load due to the reduced elastic modulus of the recycled concrete.

A gradual decrease in the coefficient of determination (R^2) was also observed as the RCA content increased, from 0.934 for the N series to 0.659 for the RC100 series. R^2 indicates the degree of agreement between the measured data and the linear model. A high R^2 value indicates that deformation is almost linear, suggesting the elastic nature of the component's operation within the given load range. A decrease in R^2 with increasing recycled aggregate content indicates a more pronounced deviation from linear behavior, which is associated with the build-up of scratches and damage to the material's microstructure. The nonlinear nature of the deformations that appear at higher proportions of recycled aggregate can be linked to earlier crack initiation and the more dynamic development of structural damage to the concrete in these series. The regression results are presented in Figure 5. The graph shows the dispersion of results as the share of RCA increases.

The results obtained confirm that it is possible to use RCA safely in slab elements without significant degradation of bearing capacity and structural stiffness, even at levels up to 20%. However, it is worth noting that significant service

Table 4. Summary of slope [mm/kN] and coefficient of determination [R^2] for different series

Series	Slope [mm/kN]	R^2
Seria N	0.285	0.934
Seria RC 20	0.38	0.787
Seria RC 50	0.397	0.705
Seria RC 100	0.369	0.659

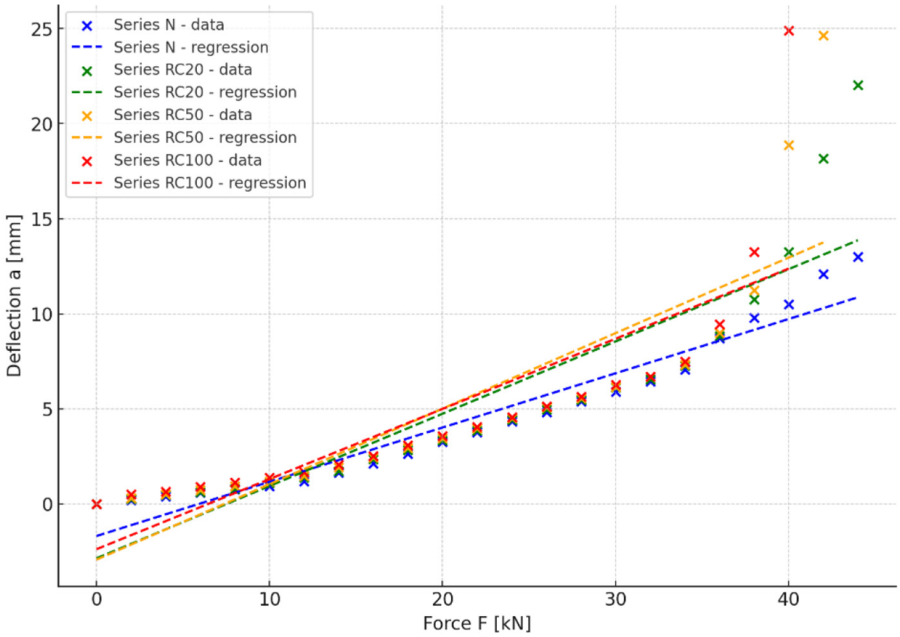

Figure 5. Linera regression of force-deflection relationship for all treated series

limitations in the form of increased deflections and earlier and more intense scratching appear at higher levels of natural aggregate replacement.

These results indicate the need for further development of suitable formulations of recycled concrete. The study could be extended to include the addition of mineral compounds, such as amorphous silica or fly ash, to improve the integrity of the cement slurry. Alternatively, the RCA aggregate could be pre-treated to remove some of the old mortar and reduce its porosity.

CONCLUSIONS

The study allowed the effect of gradually replacing natural aggregate with recycled concrete aggregate on the load capacity, deformability and cracking behavior of reinforced concrete slabs subjected to concentrated loading to be assessed. The results showed that using up to 20% recycled concrete aggregate by weight does not significantly reduce the load capacity of the elements. Compared to slabs made of concrete with natural aggregate, the decrease in bearing capacity in this group was minimal, at no more than 1%. Only when the proportion of RCA was increased above 50% did noticeable decreases in bearing capacity occur, reaching up to approximately 12% when natural aggregate was fully replaced. In terms of deformability, a systematic increase in slab deflection was observed as the proportion of RCA increased, particularly in the final loading phases. When natural aggregate was completely replaced, deflection values were almost double those of the reference slabs.

The results obtained confirm that using RCA in structural concrete production is fully acceptable, provided its proportion in the mix does not exceed moderate levels. The study showed that substituting up to 20% of natural aggregate with RCA does not affect the safety or functionality of the structure, if the mechanical and performance properties remain at an acceptable level. Research has demonstrated the potential of recycled aggregate concrete for use in structural applications. However, fully integrating it into engineering practice safely requires further optimization studies and the development of detailed design guidelines that consider the material's specific characteristics.

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