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Punching shear strength of reinforced recycled concrete slabs

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HIGHLIGHTS

- Experimental punching shear behaviour of reinforced recycled concrete slabs.
- The recycled aggregates are obtained by waste of concrete which has unknown property.
- The recycled aggregates do not influence the experimental punching shear strength.
- The theoretical punching shear models are reliable also for recycled concrete.

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ABSTRACT

This paper reports on the experimental assessment of the punching shear behaviour of reinforced recycled concrete slabs characterized by fine natural aggregates and coarse recycled aggregates. In particular, the latter were obtained only from demolished concrete. The experimental campaign has been carried out on 12 specimens. Moreover, three reinforced natural aggregate concrete slabs have been casted and tested as benchmarks. Four replacement percentages (30, 50, 80 and 100%) of coarse recycled aggregates in place of coarse natural aggregates have been considered. The punching shear behaviour of simply supported reinforced recycled concrete slabs under a central patch load has been investigated by means of failure patterns, ultimate loads and deflection–load curves.

Moreover, comparisons and a review of international code models for slabs under punching shear have been developed. The results show a reduction in recycled concrete mechanical performance with increasing replacement percentage of natural aggregate with coarse recycled aggregates. However, the reduced recycled concrete performance does not translate directly to the punching shear strength of reinforced recycled concrete slabs; indeed, the punching forces of all recycled concrete slabs tested are very similar to those of slabs realized with ordinary reinforced concrete. Actually, although the theoretical models on the punching shear are based on the characteristics of the concrete, this study indicates that the reinforcement role is of paramount relevance.

1. Introduction

Concrete is the world's most commonly used construction material, but the high use of Natural Aggregates (NA) for its production represents a significant problem regarding the preservation of natural resources [1–3]. In addition, the construction industry produces a large amount of waste every year, resulting from demolitions of constructions. Often, an important part of these wastes is composed of demolished concrete. European Policies & Strategies [4] encourage the use of recycled materials for new engineering products, so many researchers have focused their studies on the use of Recycled Aggregates (RA) from Construction Demolition Waste (CDW) in the production of new Recycled Concrete (RC) [5–16].

The benefits of using RA from recycled CDW in new concrete are known. The use of natural aggregates can be reduced, and the storage of CDW products in the landfill site could be significantly decreased, with considerable advantages to the environment. In recent years, increasing studies on the properties of RA, particularly on the properties of those from CDW waste of concrete only (RAc), have been undertaken.

Abbreviations: NA, natural aggregates; RA, recycled aggregates; CDW, Construction Demolition Waste; RC, recycled concrete; RAc, recycled aggregates from CDW waste of concrete only; CRAc, Coarse Recycled Aggregate of concrete only; NC, normal concrete; CNA, coarse natural aggregate; FNA, fine natural aggregate.

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Many studies have proved that the properties of these aggregates differ from those of natural ones [17–37]. In general, RAc are characterized by very high water absorption, lower particle density and higher Los Angeles values than NA. The main physical difference between RAc and NA is represented by the presence of the old adherent cement mortar in the surface of original NA, which is the major cause of the different properties between RAc and NA according to many researchers [17,30,32,35]. Furthermore, the sources of RAc can be very different. For the sake of synthesis, it is possible to distinguish three main categories of sources: concrete casted for that very purpose, prefabricated concrete structure production waste, and CDW waste of concrete. The characteristics of these materials cannot be easily assessed, so neither can the corresponding ones for RAc.

Many countries have established standards or recommendations regarding the properties of RA and RAc [38–42].

The structural behaviour of RC element was also investigated. Many papers have been published concerning the performance of beams and columns realized with RC [11,43–46], and studies on the seismic performance of RC frame structure – e.g. [47], – have been undertaken.

Structural systems with reinforced concrete slabs are a common structural solution. Their structural behaviour is not straightforward and has been analysed for many years, but even currently it is under investigation, particularly considering its environmental impact; see [48–52].

The slabs present several advantages such as reduced and simpler formwork, versatility and easier space partitioning, making flat slabs an economical and efficient structural system. Although simple in appearance, they present complex structural behaviour. Often, particularly for slender slabs, the critical structural assessment concerns the punching shear strength.

Actually, the punching failure mechanism is very dangerous because of its brittle nature and because it can be the origin of a progressive collapse. The first punching shear mechanical models were very complex [53–54], and the relative design formulas are very inconvenient for practical use. Many researchers have provided physical models and innovative theories [55–63] that led to simple design expressions in agreement with the most important international design code models [53,64–67]. These expressions, rationally derived based on the physical models supporting the previous theories, include some parameters obtained by a regression analysis of experimental results. A few works concerning the punching shear strength of reinforced recycled concrete slabs can be found in the literature. Sudarsana Rao et al. [68] investigated the punching shear behaviour of reinforced recycled aggregate concrete slabs. The recycled concrete was made with fine natural aggregates and coarse natural and/or recycled aggregates. RCA was obtained from the waste concrete from the runway of an Airport in Kadapa, Andhra Pradesh, India. Their results show that all slabs behaved in a similar way concerning the punching shear failure, regardless of the Coarse Recycled Aggregate of concrete only (CRAc) replacement percentage. Slabs made with RC present lower first crack load and ultimate load of slabs compared with Normal Concrete (NC). This trend was evident for RC slabs with replacement percentages greater than 40%.

Nuno Reis et al. [69] presented an experimental, numerical and analytical investigation on the effects of CRAc substitution on the punching behaviour of reinforced concrete slabs. The original concrete used to produce the recycled aggregates had the same constituents (cement, aggregates) used in the different concrete mixes tested in this study. It presented a maximum aggregate size of 22.4 mm and an average cubic compressive strength of 42.8 ± 1.3 at 28 days. The authors showed that the punching strength of the NC slabs was similar to that of the RC slabs; for 100% replacement of coarse NA by CRAc, the strength reduction was only 2%. Regarding the analytical formulae, that study showed conservative estimates of the punching strength of RC slabs for each code examined (MC 2010 [64–65], ACI 318 [66], EC 2 [67]). The most accurate predictions were obtained using MC 2010 considering levels of approximation II, III and IV.

To improve the knowledge on punching shear failure of reinforced RC slabs, this paper presents new experimental data and the corresponding analytical assessments based on international design codes [64–67]. In particular, this work analyses the feasibility of using coarse recycled aggregates obtained by concrete waste with unknown mechanical properties to realize structural elements. Indeed, the coarse recycled aggregates have been produced by crushing concrete CDW. The strength and preservation status of these concretes are unknown.

A total of fifteen slabs with different mixtures have been casted. The mixtures have been divided into five groups: 0%, 30%, 50%, 80% and 100% replacement percentage of Coarse Natural Aggregate (CNA) with CRAc. The experimental results of a punching shear test of simply supported reinforced RC slabs are reported. Failure patterns, ultimate loads and deflection–load curves of slabs under punching shear have been evaluated.

The experimental framework and the geometric and mechanical data are reported in Section 2. The experimental results of the punching shear test are reported in Section 3. Failure patterns, ultimate loads and deflection–load curves of slabs under punching shear have been evaluated.

Section 4 presents a review of the slab punching models present in the international design codes with a comparison between the predictions obtained with these models and the field data. Finally, in Section 5, conclusions are given along with several expected developments.

2. Materials and methods

2.1. Materials

Ordinary Portland cement CEM II/A-LL 42.5 R [70], locally available limestone sand as Fine Natural Aggregate (FNA), locally available CNA (limestone) and CRAc, with diameter between 4 and 12 mm, have been used.

CRAc was randomly taken from three different authorized storage sites located in south Sardinia. Thus, the strength and preservation status of the concretes used as aggregates sources is unknown.

Table 1 shows the physical properties of the FNA, CNA and CRAc (bulk density ρ_a, saturated surface dry density ρ_{ssd}, and water absorption WA_{24}). B450A steel welded mesh layers (wire diameter

Table 1
Natural and recycled aggregate properties.

Aggregates	Grading (mm)	ρ (kg/m^3)	ρ_{ssd} (kg/m^3)	WA_{24} (%)
FNA	0–4	2707	2630	2.00
CNA	4–12	2691	2600	1.40
CRAc	4–12	2630	2360	7.54

Table 2
Mix designs of concretes.

Mix	Rep%	Cem (kg)	FNA (0–4) (kg)	CNA (4–16) (kg)	CRAc (4–16) (kg)	Water (kg)	Super plasticizer (kg)
NC0	0	420	827	897	0	175	4.87
RC1	30	420	827	628	229	175	4.90
RC2	50	420	827	449	381	175	5.54
RC3	80	420	827	179	610	175	4.44
RC4	100	420	827	0	763	175	4.96