EUROCODE 2-BASED STRUCTURAL DESIGN OF A REINFORCED RECYCLED AGGREGATE CONCRETE SLAB

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ABSTRACT. This paper presents the design of a reinforced recycled aggregate concrete slab in conformity with Eurocode 2. The proposed design, similar to that of conventional structural concrete elements, differs in the application of easy-to-use correction factors accounting for the slight changes on the mechanical and durability-related performance of the new concrete caused by the incorporation of recycled aggregates. These changing parameters are considered in several scenarios involving the recycled aggregates' differing composition, quality and exposure class. Apart from these aspects, the influence of the target strength on the slab's cross-section geometry is also assessed. The results show that the proposed approach is capable of guaranteeing the serviceability and ultimate limit states taking into account the recycled aggregates' influence on the slab's mid-span deflection, main steel reinforcements and increase in cover, within the limitations imposed by Eurocode 2.

Keywords: Recycled aggregates; Sustainable construction; Construction and demolition waste; Structural concrete; Performance-based design; Eurocode 2.

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INTRODUCTION

Concrete is the World's most sought after construction material and is the basis of urban development. However, it exhibits significant environmental impacts, including the high incorporated energy from cement production and associated carbon dioxide emissions, the enormous consumption of natural resources [1] and the large quantity of debris during construction and demolition activities, i.e. construction and demolition waste (CDW) [2]. After submitting CDW to adequate separation and beneficiation techniques, the most effective approach for the maximum valorisation of these materials is the use of the resulting recycled aggregates (RA) as partial replacement to natural aggregates (NA) in the manufacture of new construction products.

The greatest challenge of manufacturing recycled aggregate concrete (RAC) is making a material with predictable performance, so that it can be used as structural elements. In previous studies, the authors have developed several practical rules for the prediction of the mechanical and durability related performance of RAC [3-11] based on the results of a meta-analysis and a systematic literature review on the matter. Working on the assumptions of those previous studies, this study presents a proposal for a performance-based design of a reinforced RAC slab in conformity with Eurocode 2 or EC2 [12]. This approach allows understanding the implications concerning the cross-section's geometry of a reinforced RAC slab and adjust it so that it is capable of guaranteeing the same service life, load bearing capacity and same long-term deformation as those of a corresponding natural aggregate concrete (NAC) slab, all within the limits established by EC2.

CHARACTERIZATION OF RA

After several beneficiation treatments in recycling facilities, three types of RA, which can be used in the production of concrete, can emerge from CDW - recycled concrete aggregates (RCA), recycled masonry aggregates (RMA) and mixed recycled aggregates (MRA) [3]. Even though the type of RA has great influence on the properties of the resulting concrete, predicting the performance solely based on the knowledge of its constituents is insufficient. For this reason, the authors developed a performance-based classification based on the aggregates' physical properties (Table 1), which, apart from being a simple and practical method for the characterization of RA, it is easily accessible to all professionals in the industry and acknowledges their categorization into several quality classes that show very strong correlations with the performance of the resulting concrete [3, 4].

Table 1 Requirements for the physical properties of aggregates for each quality class

AGGREGATE CLASS	A			B			C			D
	I	II	III	I	II	III	I	II	III	
Minimum oven-dry density (kg/m^3)	2600	2500	2400	2300	2200	2100	2000	1900	1800	No limit
Maximum water absorption (%)	1.5	2.5	3.5	5	6.5	8.5	10.5	13	15	
Maximum LA abrasion mass loss (%)	40			45			50			

DESIGN OF A RECYCLED AGGREGATE CONCRETE SLAB

In this study, a simply supported one-way RAC slab was considered (
Figure 1), with a span of 5 m, comprised of a concrete with a strength class of C30/37 or C40/50, depending on the exposure class (XC1 or XC1/XS1, respectively) [12], produced with a CEM I 42.5, with a maximum w/c ratio of 0.50 and minimum cement content of 300 kg/m^3 [13]. The choice of the model lies not only on the simplicity of calculation but on the fact that it corresponds to a fairly possible condition.

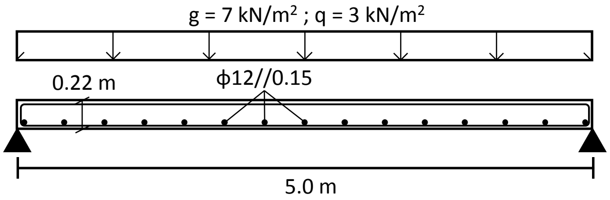

Figure 1 NAC slab cross-section (scenario 1A)

The results of the aforementioned meta-analysis carried out by the authors [4] demonstrated that it is possible to predict the compressive strength loss of RAC assuming that the RA's composition and physical properties are known and classified in accordance to Table 1.
Table 2 shows the target strength classes and compressive strength losses for each of the scenarios considered. Scenario 1 considers the design of a RAC slab with 50% RA and is based on the assumption that the introduction of RA will cause a decrease in mechanical performance. Even though this would result in strength classes inferior to those recommended by EC2, the design was further developed to understand what effects this would have on the slab's cross-section geometry. Scenario 2 corresponds to RAC made with 50% RA, but assuming that there will be no strength loss and the mix design of RAC will compensate the compressive strength loss based on the results of the statistical analysis carried out in another study [4]. In other words, there is a 95% probability that the resulting strength loss will not go beyond that of the target strength expected for the corresponding NAC and thus all mixes will be within the same strength class. For example, in scenario 2A, for a replacement ratio of 50% coarse RCA, one would need to increase two strength classes (from C30/37 to C40/50) so that the resulting RAC would show, at least, the same strength class as that of the corresponding NAC. The difference between scenarios A and B is the varying environmental exposure; in scenario A, it was defined that the structural elements would only be subjected to carbonation (exposure class XC1) and, in scenario B, chloride-related corrosion was also considered (XC1+XS1).

In scenario 1, considering the concrete mixes made with RA characterized by type, the use of RCA would result in lower compressive strength losses than when using MRA or RMA. However, carrying out a more comprehensive aggregate characterization (Table 1) would allow determining more accurately the influence of those aggregates on the properties of concrete and thus would facilitate their certification and the production of a material fit-for-industry. Indeed, RA of class A would exhibit lower strength loss owing to similarity of their properties compared to those of NA. In scenario 2, as previously mentioned, regardless of the type and class of aggregate, the resulting RAC would present the same strength class (or greater) than that of the corresponding NAC bearing in mind the compressive strength loss caused by the introduction of RA. Naturally, in order to obtain around the same compressive strength as that of the NAC, mixes comprising lower quality RA would need to be designed with a higher target strength class (e.g. more cement or lower water/cement ratio).

Table 2 Concrete strength class and mechanical performance

SCENARIO		AGGREGATE TYPE				AGGREGATE CLASS			
		NA	RCA	RMA	MRA	A	B	C	D
1A	f_{ck} (MPa)	32,5	26,3	21,9	24,4	29,1	26,3	23,7	21,9
	Strength class	C30/37	C25/30	C20/25	C20/25	C25/30	C25/30	C20/25	C20/25
	f_{ctm} (MPa)	2.90	2.56	2.21	2.21	2.56	2.56	2.21	2.21
	E_{cm} (GPa)	32.8	22.0	21.0	21.0	22.0	22.0	21.0	21.0
	$E_{c,eff}$ (GPa)	9.38	5.04	4.79	4.79	5.04	5.04	4.79	4.79
1B	f_{ck} (MPa)	42.5	34.4	28.7	31.9	38.0	34.4	31.0	28.7
	Strength class	C40/50	C30/37	C25/30	C30/37	C35/45	C30/37	C30/37	C25/30
	f_{ctm} (MPa)	3.51	2.90	2.56	2.90	3.21	2.90	2.90	2.56
	E_{cm} (GPa)	35.2	23.0	22.0	23.0	23.9	23.0	23.0	22.0
	$E_{c,eff}$ (GPa)	10.1	5.25	5.04	5.25	5.45	5.25	5.25	5.04
2A	NAC f_{ck} (MPa)	32.5	40.1	48.1	43.3	36.3	40.1	44.5	48.1
	Target class	C30/37	C40/50	C45/55	C40/50	C35/45	C40/50	C40/50	C45/55
	f_{ctm} (MPa)	2.90	2.90	2.90	2.90	2.90	2.90	2.90	2.90
	E_{cm} (GPa)	32.8	23.0	23.0	23.0	23.0	23.0	23.0	23.0
	$E_{c,eff}$ (GPa)	9.38	5.25	5.25	5.25	5.25	5.25	5.25	5.25
2B	NAC f_{ck} (MPa)	42.5	52.5	63.0	56.7	47.5	52.5	58.2	63.0
	Target class	C40/50	C50/60	C60/75	C55/67	C45/55	C50/60	C55/67	C60/75
	f_{ctm} (MPa)	3.51	3.51	3.51	3.51	3.51	3.51	3.51	3.51
	E_{cm} (GPa)	35.2	24.7	24.7	24.7	24.7	24.7	24.7	24.7
	$E_{c,eff}$ (GPa)	10.1	5.64	5.64	5.64	5.64	5.64	5.64	5.64

Since RAC presents the same relationship between mean axial tensile strength (f_{ctm}) and characteristic compressive strength (f_{ck}) to that of NAC [8], it is possible to use the already existing formulae of EC2 to estimate this property.

Table 2 presents the expected f_{ctm} of all mixes. As expected, f_{ctm} decreased alongside compressive strength in scenario 1 but remained constant throughout all mixes in scenario 2, since it is assumed that all concrete mixes would exhibit the same strength class.

Even though RAC mixes may exhibit the same compressive strength as that of control natural aggregate mixes, owing to the lower stiffness of RA, concrete specimens containing them almost always present lower moduli of elasticity (E_{cm}). This would translate into a greater deformation of a building structure and thus must be compensated by altering the mix design and/or an element's geometry. Nevertheless, by using a correction factor (α) equal to 0.7, it is possible to estimate the E_{cm} of RAC, with a 95% probability that the actual value will be higher than the calculated one [5], by means of the following formula, proposed in EC2:

$$E_{cm} = \alpha \cdot 22 \cdot \left(\frac{f_{cm}}{10}\right)^{0.3} \tag{1}$$

Where E_{cm} is the mean 28-day modulus of elasticity (GPa) and α is a correction factor, que which depends on the aggregates' nature.

To take into account creep-related deformation in a building structure, total deformation can be calculated by means of the effective modulus of elasticity ($E_{c.eff}$):

$$E_{c.eff} = \frac{E_{cm}}{1 + \alpha \cdot \varphi(\infty, t_0)} \tag{2}$$

Where α is the correction factor for the creep coefficient, φ(∞,t0), for a given time period and initial loading age (considered equal to 2.5 in this study). The correction factor α depends on the replacement ratio of RA and increases linearly up to 1.8 when the coarse aggregate fraction is completely replaced [6].
Table 2 presents the values of E_{cm} and $E_{c.eff}$ for all mixes, calculated using equations (1) and (2), respectively. These properties are significantly affected by the incorporation of RA, where decreases of around 50% can be observed for $E_{c.ef}$f.

Concerning the calculation of the concrete's cover, one must bear in mind that the magnitude of the phenomena of carbonation and chloride ion penetration increases with increasing replacement ratios. However, it is possible to correlate the coefficient for accelerated carbonation and chloride ion migration to the compressive strength [7, 9] and thus make the necessary adjustments to the cover so that it is capable of guaranteeing a pre-established service life. The relationship between the cover of RAC and NAC, with similar compositions, may be calculated using the following equations:

$$\frac{X_{RAC}}{X_{NAC}} = \left(\frac{f_{cm,NAC}}{f_{cm,RAC}}\right)^{2,7} \tag{3}$$

$$\frac{X_{RAC}}{X_{NAC}} = \sqrt{e^{-0,023(f_{cm,RAC} - f_{cm,NAC})}} \tag{4}$$

Where X_{RAC} and X_{NAC} (mm) are the affected depths of RAC and NAC, respectively, and $f_{cm,RAC}$ e $f_{cm,NAC}$ are the corresponding 28-day compressive strengths. Until further research is carried out, these equations can only be applied for concrete products produced with type CEM I cement, in accordance with EN 197 [14]. Table 3 presents the necessary nominal covers of all concrete mixes subjected to exposure classes of XC1 (scenario A) and XC1+XS1 (scenario B). The incorporation of lower quality RA and decreasing mechanical performance would mean the existence of a significantly more porous cementitious microstructure than that of the control and thus increased carbonation and chloride ion penetration. For this reason, increased cover would be required to ensure the same service life. On the other hand, in scenario 2, where the same strength class would be guaranteed by altering the mix design (by maintaining the same cement content and decreasing the amount of water), the same cover can be maintained, according to previous analyses carried out by the authors [7, 9].

In all scenarios, the design of the concrete slab was implemented by means of an iterative process, similar to that conventionally practiced for NAC concrete. After establishing the requirements of the control slab, sequential increases of 10 mm to the slab's thickness were made until all requirements were met.

Table 3 presents the solution for the lower main steel reinforcements and the cross-sections' final thickness for all scenarios. Despite the compressive strength loss in scenario 1, it did not have a significant effect on the area of steel required to guarantee the EC2's Ultimate Limit State (ULS) and, in some cases, it was possible to decrease the amount. However, this is not the case for the cross-sections' geometry. Owing to the greater deformability of RAC (noticeable in the lower $E_{c.eff}$), the slabs' thickness would have to increase to avoid significant long-term deformations and present the same deformation as that of a conventional NAC slab subjected to the same loading conditions (Figure 1). The analysis of the results of scenario 1 in Table 3 showed that the strength and stiffness loss alongside cover increase would require significant addition to the slabs' thickness. It would need to increase by 14-19% for RAC containing 50% RCA and 13-14% for 50% class A. The use of MRA and RMA would result in increases of 19-31% and 31-33%, respectively.

In scenario 2, in which the strength class would remain the same for all concrete mixes, only a slight increase to the slabs' thickness would be required, as a result of the RAC's lower stiffness. In all cases, this increase would be of only 5%, which is equivalent to an addition 10 mm.

Table 3 Cover (c_{nom}), reinforcement solution and slab thickness (D)

SCENARIO		AGGREGATE TYPE				AGGREGATE CLASS			
		NA	RCA	RMA	MRA	A	B	C	D
	c_{nom} (mm)	25	40	55	55	40	40	55	55
1A	Rebar	φ10//0.125	φ10//0.125	φ10//0.125	φ10//0.125	φ10//0.125	φ10//0.125	φ10//0.125	φ10//0.125
	D (mm)	220	250	290	290	250	250	270	270
	c_{nom} (mm)	45	55	60	55	55	55	55	60
1B	Rebar	φ12//0.15	φ10//0.125	φ10//0.125	φ10//0.125	φ10//0.125	φ10//0.125	φ10//0.125	φ10//0.125
	D (mm)	210	250	280	250	240	250	250	280
	c_{nom} (mm)	25	25	25	25	25	25	25	25
2A	Rebar	φ10//0.125	φ12//0.20	φ12//0.20	φ12//0.20	φ12//0.20	φ12//0.20	φ12//0.20	φ12//0.20
	D (mm)	220	230	230	230	230	230	230	230
	c_{nom} (mm)	45	45	45	45	45	45	45	45
2B	Rebar	φ12//0.15	φ12//0.15	φ12//0.15	φ12//0.15	φ12//0.15	φ12//0.15	φ12//0.15	φ12//0.15
	D (mm)	210	220	220	220	220	220	220	220

CONCLUSIONS

This study is a result of an extensive systematic literature review on the use of recycled aggregates in the production of structural concrete, where there is a vast amount of experimental studies. Still, in spite of the proven technical feasibility, there are several obstacles to their use in structural applications. One of those barriers is the vague concept implicit in some specifications on the use of RA, which do not contain specific provisions for the expected physical and structural performance of recycled aggregate concrete. Therefore, by combining the results of a vast number of studies, it was possible to carry out a statistically significant meta-analysis capable of leading to strongly supported evidence-based decisions thereby increasing the viability of the proposed methods.

The classification of RA, based on their physical properties, rather than their composition alone, apart from being the most practical approach for their proper categorization, has also shown to be strongly correlated with the performance of the their resulting concrete products. The formulae resulting from the authors previous studies have shown that this method can be used to easily predict the behaviour of concrete and, by adapting it to existing codes for structural concrete, it will be easier in the future to use recycled aggregate concrete in a safer and more comprehensive manner. Indeed, the implementation of the proposed method, apart from being very conservative, also demonstrates its flexibility for a wide range of applications when compared with existing specifications, which are severely restrictive.

In the two scenarios considered this study, the first one allowed the use of RA in concrete with the same mix design as that of the control, which meant a decline in mechanical performance. The second scenario considered altering the RAC's mix design by simply adjusting the water to cement ratio, with the use of superplasticizers, so that all mixes would exhibit the same strength class. Although the first one was considered in this study with the purpose of demonstrating the adaptability of the proposed approach, the second scenario is considered to be the most viable from a practicality viewpoint, because it would only mean a slight adjustment to the structural element's geometry to reduce long-term deformations. Furthermore, even though a slight thickness increase of around 5% would be needed, which would mean additional costs and environmental impacts, it is also true that a lower amount of steel reinforcements would be required in some of those cases apart from the benefits of using recycled materials. For this reason, it would be interesting to carry out a life cycle assessment considering the aforementioned aspects.

Nevertheless, although the method presented in this paper allows the design of a structural RAC element with the same load bearing capacity, deformation and service life as those of a conventional concrete, this is only possible within the parameters mentioned throughout the study. Extrapolating the results and formulae for scenarios with cement types other than CEM I or the use of recycled aggregates as sand substitute, for example, may lead to erroneous findings, which must be further backed up by evidence. For this reason, it is important to proceed with further experimental investigation, minding the gaps in the literature, in order to adapt and create provisions in existing structural codes.

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