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Eco-efficient low cement recycled concrete aggregate mixtures for structural applications

Meika Hayles, Leandro F.M. Sanchez *, Martin Noël

Department of Civil Engineering, University of Ottawa, 161 Louis Pasteur, Ottawa, ON K1N 6N5, Canada

HIGHLIGHTS

- EMV allows the cement content decrease in RCA mixtures by accounting for the RM.
- The quality of RCA source significantly influences the quality of RCA concrete.
- EMV designed RCA mixtures present suitable hardened state behaviour but might face fresh state issues.
- A modified EMV method is proposed, enabling fresh state improvement while keeping eco-efficiency.

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ABSTRACT

Research has shown that good quality recycled concrete aggregates (RCA) can be produced for structural applications if the aggregate properties are properly considered in the mix design, especially the residual mortar content (RMC). Previous studies on RCA have generally used mixes with moderate to high cement contents, which negates many of the environmental and economic advantages of this material. In this study, the *equivalent mortar volume* (EMV) method was used to develop RCA mixes with the aim of minimizing new cement content by accounting for the RMC already present, thus improving binder efficiency. Conventional RCA mixes (i.e. 25 and 35 MPa compressive strengths) containing low cement content were developed without any chemical or mineral admixtures. A modified EMV method was proposed to overcome challenges encountered in the fresh state and an optimized 35 MPa mix was developed with a low binder intensity of 9.2 kg/m^3·MPa^{-1}.

1. Introduction

The use of recycled concrete aggregates (RCA) in civil industry is predominantly limited to non-structural applications, mostly due to concerns over material quality, mechanical properties and long-term performance. In fact, many studies have reported inferior behaviour of RCA concrete in the fresh and hardened states, as well as durability. The response of many researchers has been to suggest that RCA should not be permitted for use in concrete structures, and/or that additional cement and chemicals should be added to compensate for this behaviour.

Much of the research reported in the literature implicitly treats RCA material as *homogeneous* and directly replaces certain proportions of natural aggregate in the concrete mix design, with little to no consideration made to account for both phases of the material: namely, the original aggregate particles and the residual mortar content (RMC) that remains adhered to them. Using these procedures, some percentage of natural aggregates in a mix is replaced with an equivalent mass of RCA without modifying the mix design (except perhaps to account for the higher absorption of the aggregates) [1]. Given the high variability of both the amount and quality of the residual mortar phase from different sources of RCA, it is generally difficult or even impossible to accurately predict the fresh and hardened state properties of the new recycled concrete without accounting for this parameter, and in most situations both the strength and elastic modulus are found to be lower than similar conventional concrete (CC) mixes made with natural aggregates (NA) [1].

Among the alternatives to RCA direct replacement is the previously developed *equivalent mortar volume (EMV) method* [1]. This procedure utilizes a CC control mix to develop the proportions for an RCA mix design as a function of RMC. Previous research has shown that the EMV method can be used to obtain similar behaviour for concrete with RCA as the same control mix made

* Corresponding author.
E-mail addresses: mhayles@uottawa.ca (M. Hayles), leandro.sanchez@uottawa.ca (L.F.M. Sanchez), martinnoel@uottawa.ca (M. Noël).

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with NA [2–5]. However, these studies have typically used a CC mix with moderate to high amounts of cementitious materials (i.e. higher than 400 kg/m^3) and superplasticizer, mainly to overcome challenges in the fresh state which result when the volume of new cement paste is reduced. Considering the fact that cement production is responsible for more than 5% of CO_2 emissions worldwide [6], new approaches are needed with a more holistic view of sustainability which balances and optimizes the use of all constituent materials.

One measure of the environmental sustainability of concrete is its cement efficiency, which refers to the relationship between the cement content (in mass) used in a concrete mix design and its performance (e.g. the change in compressive strength associated with one unit increase in the mass of cement). Concrete mixes with high cement efficiency have adequate strength and suitable overall performance while using lower amounts of cement to achieve these targets. Normally cement efficiency tends to increase with concrete compressive strength, but CC mixes in the range of 25–45 MPa 28-day compressive strengths are generally not eco-efficient in this respect [7]. The objective of the current study is to explore whether the EMV method previously proposed as by [1] can be used to improve binder efficiency to produce eco-efficient RCA concrete with low carbon footprint, while still meeting performance criteria in the fresh and hardened states.

2. Equivalent mortar volume method

The EMV method is fully described in [1], but is briefly reviewed here for convenience. Table 1 summarizes all the acronyms used while the mix-design procedure for a better understanding of the EMV method. The theory behind the EMV is that all mortar and aggregates should be treated the same, regardless of whether or not they are sourced from new material or as a constituent of the RCA. RCA is comprised of two components: the original virgin aggregate (OVA) and residual mortar (RM).

The volume of total mortar in the control mix is matched by the volume of new mortar and the RM of the RCA. Similarly, the total volume of aggregates in the control mix is matched by the volume of OVA within the RCA and new NA. The mix design should meet the following criteria:

$$\mathrm{V_{FA}^{NAC} + V_{Cement}^{NAC} + V_{Water}^{NAC} = V_{RM}^{RCA} + V_{FA}^{RCA} + V_{Cement}^{RCA} + V_{Water}^{RCA}} \quad (1)$$

where $\mathrm{V^{NAC}}$ refers to the volume of a constituent within the normal aggregate concrete, $\mathrm{V^{RCA}}$ is the volume of a constituent within the RCA concrete, and subscripts FA and RM denote the fine aggregates and residual mortar respectively. The concept is to match the total volume of the mortar in the final mix design, including mortar that has already hardened.

Table 1
Acronyms used while the mix-design of RCA concrete using the EMV.

EMV Acronyms	Description
NA	Natural aggregate
CC (or NAC)	Conventional concrete (or Natural Aggregates Concrete)
RCA	Recycled concrete aggregate
OVA	Original virgin aggregate
RM	Residual mortar
RMC	Residual mortar content
EMV	Equivalent mortar volume
$\mathrm{RMC_{max}}$	Maximum residual content permitted in the RCA
$\mathrm{V^{NAC}}$	Volume of a constituent within the CC
V_{NA}^{NAC}	Unit volume of NA within the CC
V_{OVA}^{RCA}	Unit volume of OVA within the RCA
V_{NA}^{RCA}	Volume of new aggregate in the RCA mix
V_{RM}^{RCA}	Volume of residual mortar in the RCA
V_{NM}^{RCA}	Volume of new mortar in the RCA
W_c^{NAC}	Weight of cement in the CC
W_c^{RCA}	Weight of cement in the RCA
W_{FA}^{NAC}	Weight of fine aggregates in the CC
W_{FA}^{RCA}	Weight of fine aggregates in the RCA

The design principles of the EMV employ a limiting technique to restrict the upper limit of RM on the RCA that can be used for design. For example, if the RCA is comprised only of residual mortar, it will be impossible to satisfy Eq. (1). The maximum permissible design RMC content defined by [1] is given by the equation below:

$$\mathrm{RMC_{max} = 1 - V_{DR-NA}^{NAC} \cdot \left(SG^{NA}/SG^{RCA}\right)} \quad (2)$$

$\mathrm{RMC_{max}}$ can be correlated with a value $\mathrm{R_{min,}}$ the minimum percentage value of NA required in the RCA mix design. After determining the RMC of the RCA, the desired replacement percentage is selected, ensuring that this value is less than the calculated maximum. A unit volume of NA in the control mix is then matched with the unit volume of OVA within the RCA such that the following condition is met:

$$\mathrm{V_{OVA}^{RCA} = V_{NA}^{NAC} - V_{NA}^{RCA}} \quad (3)$$

where V_{OVA}^{RCA} is the unit volume of OVA within the RCA, V_{NA}^{NAC} is the unit volume of NA within the control mix and V_{NA}^{RCA} is the volume of new aggregate in the RCA mix.

Knowing the unit weights of each component, W^{NAC}, and volumes, V^{NAC}, needed for the control mix, the volumes of RCA and NA in the RCA mix can be calculated as follows:

$$V_{RCA}^{RCA} = V_{NA}^{NAC} * (1 - R)/[(1 - RMC)SG_{OVA}/SG_{RCA}] \quad (4)$$

$$V_{NA}^{RCA} = R * V_{NA}^{NAC} \quad (5)$$

The remaining volume within a unit of concrete must then be comprised of mortar, either new mortar (NM) or residual mortar (RM), and can be calculated as follows.

$$V_{RM}^{RCA} = V_{RCA}^{RCA}(1 - (1 - RMC)SG_{RCA}/SG_{OVA}) \quad (6)$$

$$V_{NM}^{RCA} = 1 - V_{RM}^{RCA} - V_{NA}^{NAC} \quad (7)$$

Once the required volume of new mortar is known, the components of the mortar are proportioned using the ratio of required new mortar in the RCA design to the total mortar in the control mix.

$$W_c^{RCA} = W_c^{NAC} * V_{NM}^{RCA}/V_{TM}^{NAC} \quad (8)$$

$$W_{FA}^{RCA} = W_{FA}^{NAC} * V_{NM}^{RCA}/V_{TM}^{NAC} \quad (9)$$

where W_c^{RCA} is the weight of cement in the RCA mix, W_c^{NAC} is the weight of cement in the control mix, W_{FA}^{RCA} is the weight of fine aggregates in the RCA mix and W_{FA}^{NAC} is the weight of the fine aggregates in the control mix.

3. Research significance

RCA provides a sustainable alternative to the production of new aggregates and help reducing the impact of construction waste generated during the demolition of existing infrastructure. Lack of knowledge about its behaviour has led to misconceptions about the performance and durability of RCA concrete. Furthermore, to the authors' knowledge, the use of RCA and the EMV method as a means to increase binder efficiency has not been explored to date. This research focuses on a holistic approach to the sustainable design of RCA concrete by using residual mortar to reduce the cement content of new mixes, helping support a better knowledge and understanding of this eco-friendly material.