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Comparative analysis of existing prediction models on the creep behaviour of recycled aggregate concrete

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A B S T R A C T

This paper provides a systematic literature review, based on the identification, appraisal, selection and synthesis of publications relating to the effect of incorporating recycled aggregates sourced from construction and demolition wastes, on the creep behaviour of concrete. It identifies various influencing aspects related to the use of recycled aggregates such as replacement level, size and origin, as well as mixing procedure, exposure to different environmental conditions, use of chemical admixtures and additions, and creep of recycled aggregate concrete after unloading. A statistical analysis on the collated data is also presented with the purpose of understanding the creep behaviour of concrete, based on the replacement level of recycled aggregates. The evidence gathered was also compared to a model for compliance prediction. Correction factors of the creep coefficient of concrete with varying recycled aggregate content are presented in this paper. Some of the prediction models are feasible for use in recycled aggregate concrete.

1. Introduction

The increasing and unsustainable consumption of natural resources, along with the excessive production of construction and demolition waste (CDW), has been the cause of great concern for the environment and economy. In order to reverse this trend, there have been several efforts to promote ecological efficiency in the construction industry, one of them being the reutilization of CDW in new construction.

1.1. Background

The global market for construction aggregates is expected to increase 5.2% per year until 2015, up to 48.3 billion tonnes [1]. In the USA, the EPA [2] estimated that the generation of debris, from construction, demolition and renovation of residential and non-residential buildings in 2003, was close to 170 million tonnes. According to Eurostat [3], the total amount of waste generated in the EU, in 2010, was over 2.5 billion tonnes, of which almost 860 million tonnes belonged to construction and demolition activities. Bearing this in mind, the use of recycled aggregates (RA) as replacement for natural aggregates (NA) in the production of concrete has been considered as one of the most efficient methods for recycling certain materials from CDW and thus contributing to a greater sustainability in construction. Research on this subject started with basic observations on the effects of using recycled concrete aggregates (RCA) on the strength of concrete [4,5], as well as its economic feasibility [6,7]. Since then, research on recycled aggregate concrete (RAC) has become progressively complex, introducing several new variables, in which the rheology and durability-related performance have also been considered.

1.2. Recycled aggregates from construction and demolition waste suitable for the production of structural concrete

According to existing specifications [8–23], there are three main types of materials arising from CDW, which after undergoing proper beneficiation processes in certified recycling plants are suitable for the production of structural concrete. Some of these specifications [12,17,18,20] have reached a consensus that, in order to be considered as RCA, these must comprise a minimum of 90%, by mass, of Portland cement-based fragments (from crushed concrete) and NA.

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RA sourced from crushed masonry, or recycled masonry aggregates (RMA), may include: aerated and lightweight concrete blocks; ceramic bricks; blast-furnace slag bricks and blocks; ceramic roofing tiles and shingles; and sand-lime bricks [24]. RMA are composed of a minimum of 90%, by mass, of the summation of the aforementioned materials.

Aggregates acquired from mixed demolition debris, or mixed recycled aggregates (MRA), are a mixture of the two main components obtained from the beneficiation process of CDW: crushed and graded concrete and masonry rubble. Some specifications [10,18] state that it is composed of less than 90%, by mass, of Portland cement-based fragments and NA. In other words, it may contain other common CDW materials such as masonry-based materials.

1.3. Research goal

The scope of this investigation was to bring together, analyse and evaluate the published information on the effect of RA on the creep behaviour of concrete. A statistical analysis was also performed on the collated creep data from several studies, in order to comprehend the effect of introducing increasing amounts of RA on this property. The results of this analysis were then compared to recommendations of existing specifications, to understand whether these can be applied when designing concrete for structural applications as per EC2 [25]. The authors also set out to determine whether existing prediction models may be used to predict the compliance of RAC.

2. Influencing factors on the creep of recycled aggregate concrete

According to EC2 [25], creep is a rheological property of concrete. It is one of the two time-dependent deformations that concrete experiences in structures. Generally, its effects on concrete must be considered in structural design, to check compliance with Serviceability Limit States (SLS) and, in some cases, Ultimate Limit States (ULS). The various properties' definitions and notations related to this phenomenon can be found in Table 1.

Deformation of concrete due to creep is a complex phenomenon, which is influenced by many factors including the mix design, environmental conditions (i.e. temperature and relative humidity), load conditions and the size of the structure or member [26].

The cement paste of concrete, when exposed to natural environmental conditions (normally below saturation), will not retain its dimensions. This is mostly because of the loss of water in the formation of calcium silicate hydrates (C–S–H) [26,27], resulting in shrinkage strain. Similarly, when a hydrated cement paste is subjected to stress, depending on its level and extent, C–S–H will lose a large amount of the physically absorbed water and the paste will suffer creep strain.

A recent investigation [28] showed by means of statistical nano-indentation testing that C–S–H creep may be due to nano-particle sliding. In the presence of sustained loading, it is possible that nano-particles slide, thus leading to a local increase of the packing density towards the jammed state associated with limit packing densities, beyond which no particle sliding is possible without dilation of the granular media. The literature review has shown that there are various ways of designing and producing concrete using RA. In the following sections, it was the authors' aim to identify and appraise the main issues related to the use of RA, which may affect the creep behaviour of concrete.

2.1. Recycled aggregate replacement level

In order to evaluate the influence of adding increasing amount of RA on the concrete creep, significant amount of data were collected from several publications, which have been presented in different forms, i.e. creep coefficient, specific creep and creep strain. Coming from different sources and reflecting different degrees of control, some of the data have shown considerable scatter. Nevertheless, the literature review showed a constant trend of increasing creep caused by increasing RA content.

Fig. 1 plots the relative creep strain and creep coefficient of unsealed concrete specimens with increasing coarse RA content at the end of the test. Table 2 shows the type of cement, *w*/*c* ratio and the creep test conditions for each of the series of results in Fig. 1. A statistical analysis of the results in Fig. 1a showed high coefficients of determination (R^2) in most concrete mixes. Furthermore, the coefficients of correlation (or Pearson's *r*), which were between 0.95 and 0.99 demonstrate a very strong linear relationship between the two variables. This suggests that one can expect linear increases in creep deformation with increasing coarse RA replacement level, although it is also possible that there may be a steep increase in creep deformation followed by stabilization (resembling a hyperbolic trend). In the case of Domingo et al. [29,30] for example, introducing RCA, which were not water compensated, led to a lower effective *w*/*c* ratio and thereby increased strength. The use of 100% coarse RCA content led to a compressive strength increase of about 20% for concrete of design strength of 45 MPa. For this reason, it is difficult to ascertain whether this limited the increase in creep.

The results obtained by Bravo et al. [31] showed relatively greater creep strains with increasing replacement levels. Since the author used MRA as coarse aggregates, it is possible that their lower stiffness, in comparison to that of RCA, may have been the cause of this greater deformability.

The results from more recent literature were consistent with those presented by the comprehensive state-of-the-art report produced by Hansen [24] and other publications [23,32,33]. These have shown that the use of 100% coarse RA normally causes concrete to exhibit up to 60% greater creep than a corresponding NAC. However, considering the scarcity of reports on the effect of

Table 1
Definition and notation of properties related to creep of concrete.

Property	Description	Equation
Total load-induced strain	Total change in length per unit length measured in a concrete specimen under a sustained constant load applied at age t_0 at uniform temperature	$\varepsilon(t,t_0)=\varepsilon_i(t_0)+\varepsilon_c(t,t_0)$ (1)
Initial strain	Short-term elastic strain at the moment of loading	$\varepsilon_i(t_0)=\frac{\sigma}{E_{cmt_0}}$ (2)
Creep strain	Time-dependent increase in strain under constant load taking place after the initial strain at loading	$\varepsilon_c(t,t_0)=\phi(t,t_0)\frac{\sigma}{E_{cmt_0}}$ (3)
Creep coefficient	Ratio of the creep strain to the initial strain	$\phi(t,t_0)=\frac{\varepsilon(t,t_0)}{\varepsilon_i(t_0)}-1$ (4)
Compliance	Total load induced strain at age *t* per unit stress caused by a unit uniaxial sustained load applied since loading age t_0	$J(t,t_0)=\frac{\varepsilon_i(t_0)+\varepsilon_c(t,t_0)}{\sigma}$ (5)
Specific creep	Creep strain per unit stress	$\varepsilon_{c,sp}(t,t_0)=\frac{\varepsilon_c(t,t_0)}{\sigma}$ (6)