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Tensile strength behaviour of recycled aggregate concrete

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HIGHLIGHTS

- State of the art review on the effect of recycled aggregates on tensile strength.
- Use of EC2 prediction model to estimate tensile strength of recycled aggregate concrete.
- Proposal of coefficients, compatible with EC2, for tensile strength gain over time.
- Relationship between the tensile and compressive strength of recycled aggregate concrete.
- The relationship proposed in EC2 is followed by recycled aggregate and conventional concretes.

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ABSTRACT

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 tensile strength 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, chemical admixtures, additions and strength development over time. In this paper, estimated values, using the Eurocode 2 method to determine the tensile strength over time, were compared with the actual measured values, showing little correlation and therefore new coefficients are proposed. This paper also presents the relationship between the tensile and compressive strengths according to Eurocode 2. The results suggest that, regardless of the replacement level, type, and quality of the recycled aggregate used, the resulting recycled concrete tends to exhibit a similar relationship to that of the corresponding natural aggregate concrete.

1. Introduction

Vast amounts of waste materials are produced by the construction and demolition industry every year [1]. The volume of these materials has reached an unacceptable point for environmental, economic and social reasons. These issues may be addressed by means of more proactive approaches, which include recovery, reuse and recycling techniques, and facilities.

It takes many years for a waste management system to develop into a sustainable, reliable, skilful and marketable industry, encouraging the reuse and recycling of components and materials. It is necessary that all parties involved (i.e. clients, contractors, planners and manufactures) play their role in achieving a more sustainable approach. This can be done by extending the life cycle of materials, components and resources. The use of recycled materials in high rather than low-grade applications must also be a priority in the near future. In order to be successful in this approach, the correct choice of materials, recycling procedures and manufacturing processes is fundamental.

1.1. Background

The characteristics of construction and demolition waste (CDW), such as quantity, potential quality and true cost, are often overlooked. This lack of awareness leads to the disposal of great amounts of potentially recyclable materials, only to be replaced with similar conventional components. Applying recycling and beneficiation procedures to CDW is considered one of the most effective measures to reduce the ecological footprint caused by

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the construction industry, especially when used as replacement for natural aggregates (NA).

Professionals in the construction and demolition industry still often see the concept of selective demolition as being of debateable economic benefit and little practical value. Nevertheless, a detailed economic analysis of conventional *versus* selective demolition [2] showed that, in spite of the economic viability of selective demolition depending largely on labour costs, tipping fees, and market prices for recovered materials, it may ultimately be more profitable than the conventional demolition approach. Furthermore, from an environmental point of view, there are clear benefits from using selective demolition, namely in a direct reduction in the material sent to landfill [3,4] as well as other environmental impacts (i.e. climatic change, acidification, summer smog, nitrification and amount of heavy metals [5]).

The use of recycled aggregates (RA), as replacement for NA, in construction applications has been considered as one of the cleanest approaches for recycling given materials from CDW, thus contributing to a greater sustainability in construction. Indeed, extensive scientific research and development work on this subject has been carried out over the last 40 years, which has been becoming increasingly complex, introducing several new variables, in which the durability-related performance has also been considered.

1.2. Recycled aggregates sourced from construction and demolition wastes

After being subjected to proper beneficiation processes in certified recycling plants, according to existing specifications [6–21], there are three main types of RA arising from CDW that are suitable for the production of structural concrete. These materials are derived from crushed concrete, crushed masonry, and mixed demolition debris.

Recycled concrete aggregates (RCA), which is the most commonly studied recycled material in concrete production, must comprise a minimum of 90%, by mass, of Portland cement-based fragments and NA, according to some of the aforementioned specifications [10,15,16,18].

RA sourced from crushed masonry may be classified as recycled masonry aggregates (RMA) and are composed of a minimum of 90%, by mass, of the summation of the following materials: aerated and lightweight concrete blocks; ceramic bricks; blast-furnace slag bricks and blocks; ceramic roofing tiles and shingles; and sand-lime bricks [22].

Mixed recycled aggregates, or MRA, are a mixture of the two aforementioned components, acquired from mixed demolition debris, after the beneficiation process. Some specifications [8,16] state that they are composed of less than 90%, by mass, of Portland cement-based fragments and NA. In other words, they 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 in-formation on the effect of several factors related to the use of RA on the tensile strength of concrete. A statistical analysis was also performed on the collated data from several studies, in order to understand the effect of introducing an increasing amount of RA on this property. Furthermore, the authors also sought to understand the tensile strength development of recycled aggregate concrete (RAC) over time by using the model proposed in EC2 [23] and assess its potential enhancement, by means of a multiple linear regression. Finally, the relationship between the tensile and compressive strengths was also studied, since it constitutes the main approach for concrete producers and designers to estimate the tensile strength of concrete.

2. Influencing factors on the flexural and splitting tensile strength of recycled aggregate concrete

According to the brittle fracture theory, failure of a specimen is initiated through the largest crack oriented in the direction normal to the applied load. This makes the occurrence of such a crack a stochastic problem, in which the size and shape of the specimen are factors that affect strength, since there is a higher probability of a larger specimen containing a greater number of critical cracks, which can initiate failure [24]. In the case of concrete, the energy released at the onset of cracking may not be sufficient to continue the propagation of a crack because it may be blocked by a large pore or a more ductile material, which requires more energy to fracture.

The influence of the aggregate shape is more apparent in the flexural strength test than in the compressive or splitting tensile strength tests, probably because of a stress gradient that delays the progress of cracking leading to ultimate failure. Therefore, concrete with angular-shaped aggregates will normally exhibit higher flexural strength than when round-shaped aggregates are used, especially in mixes with low w/c ratios. However, to achieve the same workability, round-shaped aggregates require less water than angular-shaped aggregates, and thus the flexural strengths of the two concretes are similar [24].

It is suggested that the type of aggregate has little influence on the direct and splitting tensile strengths, but the flexural strength of concrete is greater when angular crushed aggregate is used than with rounded natural gravel [24]. This can be explained by the improved bond between the angular-shaped crushed aggregate and the cement paste. This, however, does not occur with crushed flint gravels, which normally result in a low tensile strength due to poor bond with the glassy flint surfaces [25]. The interfacial transition zone (ITZ) between this type of aggregate and hydrated cement paste may exhibit few mechanical bonds, thus leading to greater probability of failure.

The aggregates' size also affect the tensile strength concrete, which tends to be higher when using finer aggregate fractions, due to the increase in aggregate's surface area and hence reduction in aggregate-cement paste bond stress [25].

Generally, RAC tends to exhibit lower tensile strength when compared to that of the corresponding natural aggregate concrete (NAC), and the magnitude of the difference depends on several factors related to the use of RA that are discussed in the following sections.

2.1. Recycled aggregate replacement level

The literature review shows a consensus in that, as the replacement level increases, the tensile strength decreases. This was observed in all publications studied [26–66]. Fig. 1 presents the relative splitting tensile strength of concrete with increasing amounts of coarse and fine RA, regardless of type and quality. Although there is a clear trend that the inclusion of RA leads to lower splitting tensile strengths when compared to that of the control concrete, in a few cases RAC exhibited similar or even slightly greater strength. Since this was observed mostly for specimens containing RCA, it is possible that the bond strength in the ITZ,