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# Long-term behaviour of reinforced beams made with natural or recycled aggregate concrete and high-volume fly ash concrete

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## HIGHLIGHTS

- Six simply supported reinforced concrete beams tested under sustained load.
- Natural aggregate, recycled aggregate and high-volume fly ash concrete tested.
- Deflections for all six beams doubled during 450 days under sustained load.
- Results compared with code predictions and existing results from literature.

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## ABSTRACT

Six simply supported reinforced concrete beams were tested under sustained loads for 450 days. The beams were made from natural aggregate concrete (NAC), recycled aggregate concrete (RAC) and high-volume fly ash concrete (HVFAC); two beams were made from each concrete and loaded after 7 and 28 days. On the beams, deflections, cracking and strains were measured while concrete specimens were used to determine physical-mechanical properties of concretes and measure shrinkage and creep. Results showed similar increases in deflections relative to initial deflections for all six beams. The results are also compared with code predictions and with existing results in literature.



## 1. Introduction

The research community has been investigating possible solutions to environmental issues of concrete production. As the world's most-used construction material, almost 20 billion tons of concrete are produced annually worldwide [1]. This huge amount of concrete requires equally large amounts of its component materials: 15 billion tons of aggregates (river or crushed stone) [2] and 4.2 billion tons of cement [3]. Although concrete has a low embodied energy compared with other materials, the scale of its use means a significant impact on the environment.

The first impact is through the production of cement. Using current practice, each kg of cement produced is associated with an average of 842 g of $CO_2$; taking into account global annual cement production, the cement industry is actually responsible for 7–10% of all anthropogenic $CO_2$ emissions [4]. The second significant impact of concrete is its end-of-life, i.e. what happens after any concrete, plain or reinforced, has been decommissioned and demolished. Currently, most of it is still simply landfilled. What remains after the demolition of concrete structures is construction and demolition waste (CDW): in the EU alone, around 850 million tons of CDW are generated annually, accounting for approximately 30% of total waste generated [5].

One promising solution for these problems is the recycling of CDW to produce recycled aggregates in order to replace river or crushed stone aggregates in concrete production. This approach has the benefit of saving natural resources and reducing the amount of CDW being landfilled. A second potential solution is the partial replacement of cement by supplementary cementitious materials, usually industrial by-products. This approach both saves natural resources but also reduces the use (and indirectly production) of cement, thus potentially lowering $CO_2$ emissions.

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As for recycling CDW, it can be performed on several materials, such as masonry and concrete. When concrete (plain or reinforced) is recycled, the produced aggregates are called recycled concrete aggregates (RCA). The content of other CDW (masonry, asphalt, glass, wood, etc.) must be kept very low, e.g. 10% [6]. Since concrete is composed of natural aggregates bound by hardened cement mortar, after crushing concrete waste, the final product, RCA, is composed of natural aggregate particles with some 'residual cement paste' bound to them. This 'residual cement paste' is one of the defining characteristics of RCA and it influences most of its properties: RCA generally has lower density, higher porosity and greater water absorption compared with natural (both river and crushed stone) aggregates (NA) [7–9].

When RCA is used to produce concrete, this new concrete is called recycled aggregate concrete (RAC) and its use has been investigated for several decades [10]. So far, RCA has mostly found its way to use in applications such as road sub-base and non-structural concretes; only 1% of aggregates used in the production of structural concrete is RCA [11]. However, true recycling of CDW must lead to greater use of RCA in structural applications. In this study, RAC will refer to concrete in which only coarse aggregates (particle size >4 mm) are replaced with RCA.

RAC has been very comprehensively investigated. The research on RAC has mostly focused on short-term mechanical and durability-related properties: compressive strength, tensile strength, modulus of elasticity, carbonation resistance, chloride ion penetration, etc. Comprehensive literature reviews analysing these properties of RAC compared with companion natural aggregate concrete (NAC)—usually defined as having the same water-cement (w/c) ratio—were published in recent years [12,13]. The general conclusion from these literature reviews is that mechanical properties of RAC with 100% replacement of coarse aggregate with RCA are, on average, lower than those of companion NAC (20–40% for compressive strength, 20% for tensile strength and 30% for the modulus of elasticity) [12,13].

A topic that has been less investigated is the shrinkage and creep behaviour of RAC. RCA exerts several influences on these properties in RAC: since RCA is usually weaker than NA, it provides less restraint for shrinkage and because of the residual cement paste on RCA particles, RAC usually has a larger total volume of cement paste compared with companion NAC leading to greater shrinkage and creep. Several literature reviews on studies of shrinkage and creep of RAC have been published [12,14,15]: studies covered in these literature reviews systematically found larger shrinkage and creep strains for RAC compared with companion NAC – for RAC with 100% replacement of coarse aggregates the increases in shrinkage and creep relative to companion NAC can be expected to be 20–50% and 20–60%, respectively.

One option for partial cement replacement is fly ash, a by-product of coal combustion in thermal power plants. Fly ash has pozzolanic properties and is produced globally in large quantities – 900–1000 megatons annually [4]. When fly ash is used in the production of concrete in which it constitutes more than 50% of total cementitious materials, then such a concrete is called high-volume fly ash concrete (HVFAC) [16]. For HVFAC, studies are less comprehensive and more difficult to methodologically carry out because fly ash is a by-product of coal combustion and its physical properties can vary considerably, depending on the coal from which it originated and the technological process employed in the thermal power plant. The properties of fly ash with the greatest influence on HVFAC properties are the particle size distribution and chemical composition. The mean particle size of fly ash can vary from 1 to 100 μm, with a typical size of around 20 μm [17]. One possible distinction between different types of fly ash is based on the criterion of the American standard ASTM C618-12 [18]: if the sum of silicon, aluminium and iron oxides in fly ash is greater than 70%, the fly ash is defined as class F, otherwise as class C.

One literature review available for HVFAC has been published recently [17]. For compressive strength, HVFAC with 45–55% of fly ash in total cementitious materials on average has around 60% of the compressive strength of companion NAC produced with the same water-cementitious materials ratio (w/cm) after 28 days and around 75% after 90 days [17]. Reductions were also found in tensile strength and modulus of elasticity: 35–45% reductions for HVFAC with 45–55% of fly ash in total cementitious materials; the decrease in the modulus of elasticity was found to be between 10% and 60% [17].

The effect of fly ash on shrinkage is mostly beneficial: one literature review revealed that drying shrinkage of HVFAC can be reduced up to 50% for fly ash contents of 50% of total cementitious materials [17]. The lower shrinkage of HVFAC compared with companion NAC was also explained as a result of reduced cement paste content and a lower amount of hydrated paste (caused by the slower pozzolanic reaction) [19]. For creep, similar trends can be expected. When comparing HVFAC and companion NAC proportioned to have the same strength at the time of loading, HVFAC will exhibit lower creep due to the larger increase in compressive strength [20].

As stated earlier, in order to achieve the full potential of both RAC and HVFAC, they have to find their way to use in structural applications. There is a considerable number of studies investigating the structural behaviour of these two concrete. The most numerous are studies testing the ultimate flexural and shear strength of RAC [21–26] and HVFAC [27–29] beams; in the case of RAC, there are even studies on structures, such as static push-over or dynamic shake-table tests [30,31]. For RAC and HVFAC structural members, the studies generally don't find any significant difference in ultimate loads compared with companion NAC members. However, for both concretes, differences are found compared with companion NAC in terms of cracking and deflections. Because of weaker aggregates in RCA, cracking and short-term deflections are greater for RAC members compared with companion NAC members [22,23]; for HVFAC members, authors noted no significant differences compared with companion NAC or even lower short-term deflections and less cracking [28,29].

A topic that has been much less researched is the long-term behaviour of reinforced RAC and HVFAC members under sustained loads even though the need for taking their different long-term behaviour into account in design has been recognized [32]. The problem of serviceability, namely deflections, of reinforced concrete structures is often overlooked but not unimportant [33,34]: controlling appearance, preventing damage to non-structural elements and loss of utility are strong reasons for not disregarding this issue. However, because of the difficulty of adequately carrying out such tests and because of many factors which influence deflections, these tests are not numerous, even for NAC [35,36].

There is only a small number of long-term tests on reinforced RAC beams [21,37–42] and no tests on HVFAC beams. Unfortunately, many of the studies on RAC beams are published in the form of conference proceedings and often do not offer sufficient information. The studies vary in properties of used RCA (with water absorption from 1.9% to 6%), geometric properties of the beams (spans 2000–3700 mm, beam height 200–300 mm, reinforcement ratio 0.5–1.6%) and duration of sustained load (118–1000 days). The authors generally find larger deflections and greater cracking in RAC beams compared with companion beams produced from NAC with an identical w/c ratio as RAC [38,40,41]. Although some authors also test the applicability of existing design code provisions for deflections [43,44] to RAC beams [40], the existing number of experimental results is not sufficient for conclusive remarks.