Sryh and Forth *Int J Concr Struct Mater* (2022) 16:19
https://doi.org/10.1186/s40069-022-00512-0

International Journal of Concrete Structures and Materials

RESEARCH Open Access

Long-Term Flexural Behaviour of Cracked Reinforced Concrete Beams with Recycled Aggregate

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Abstract

This paper presents the results of an investigation into the long-term flexural behaviour of cracked reinforced recycled aggregate concrete (RAC) beams. Washed construction and demolition wastes (CDW) with a maximum size of 20 mm were used as the coarse recycled aggregate. The main variable in the research was the replacement ratio of recycled aggregate. Specimens with 0%, 50% and 100% recycled aggregate were cast and tested. The experimental results showed that samples with an increased amount of recycled aggregate had significantly reduced strength and a noticeable increase in both short-term and long-term deflection of RAC beams over equivalent normal concrete (NC) beams. Increased levels of RA resulted in greater creep and shrinkage of RAC and greater long-term loss of tension stiffening in RAC reinforced tension specimens. Prediction of long-term deflections using Eurocode 2, even after incorporating the experimental concrete properties within the Code method, underestimated the experimental deflections of the RAC beams. However, by modifying the tension stiffening factor, β used in Eurocode 2, deflections were predicted to within approximately 1%. From this investigation, it is recommended that the factor β be reduced from 0.5 (for NC) to 0.4 (for RAC @50% replacement) and 0.3 (for RAC @100% replacement).

Keywords: reinforced concrete beams, recycled aggregate concrete, flexural behaviour, long-term deflection, creep and shrinkage, tension stiffening

1 Introduction

Concrete is the most common structural material and has been used in all types of construction work. It has been reported that approximately 10 billion tonnes of concrete are consumed annually worldwide, the corresponding quantity of aggregate, which is the main component of concrete, is in the range of 8–12 billion tonnes (Brito & Saikia, 2012; Kishore, 2007).

Besides the environmental concern posed by the CO_2 emissions from cement production, the continued growth in demand for concrete raises other concerns: first, the availability of the natural resources for its component materials and second, the vast size of the landfills required for disposing of the construction and demolition waste. These factors mean that concrete is not an environmentally friendly construction material. Therefore, a significant amount of research (Ajdukiewicz and Kliszczewicz, 2007; Arezoumandi et al., 2015; American Concrete Institute, 2004; Brito and Saikia, 2012; Etxeberria et al., 2007; Ignjatović et al., 2013; Kishore, 2007; Kosior-Kazberuk and Grzywa, 2014; Maruyama et al., 2004; Rahal, 2007; Sato et al., 2007; Sryh and Forth, 2015; Yang et al., 2008) has been conducted to assess how construction and demolition wastes (CDW) can be reused as recycled aggregate (RA) for producing recycled aggregate concrete (RAC) and also how to use RAC for structural applications. There has been little research on the serviceability behaviour of reinforced concrete incorporating CDW; much of the general research in this area (Brito & Saikia, 2012; Juan & Gutiérrez, 2009; Knaack

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& Kurama, 2015; Łapko & Grygo, 2010; Maleśev et al., 2010) has used recycled concrete aggregate (RCA) only.

Previous research (Ajdukiewicz and Kliszczewicz, 2007; American Concrete Institute, 2004; Arezoumandi et al. 2014, 2015; Brito and Saikia, 2012; British Standards Institution, 2004; Choi and Yun, 2013; Etxeberria et al., 2007; Ignjatović et al., 2013; Juan and Gutiérrez, 2009; Kishore, 2007; Knaack and Kurama, 2015; Kosior-Kazberuk and Grzywa, 2014; Łapko and Grygo, 2010; Maleśev et al., 2010; Maruyama et al., 2004; Michaud et al., 2016; Rahal, 2007; Sato et al., 2007; Sryh and Forth, 2015; Wardeh and Ghorbel, 2019; Xiao et al., 2005; Yang et al., 2008) has shown that all the types of recycled aggregate in general has a greater effect on the time-dependent deformation than on the short-term behaviour and strength properties of concrete. There is a noticeable increase in creep and shrinkage when any type of RA is incorporated in concrete, which affects the long-term flexural behaviour of concrete structures. To date, the influence of the different types of RA on tension stiffening over time, which is a parameter required to calculate long-term deflections, has not been addressed.

2 Background

In order to determine the scope for the future use of RA as a construction material, the physical and mechanical properties of RAC have attracted a significant amount of interest in recent research. Based on the available experimental results, incorporating the different types of RA in concrete has the following effects on the mechanical properties (Brito & Saikia, 2012; Etxeberria et al., 2007; Juan & Gutiérrez, 2009; Kishore, 2007; Kosior-Kazberuk & Grzywa, 2014; Maleśev et al., 2010; Rahal, 2007; Sryh & Forth, 2015; Xiao et al., 2005; Yang et al., 2008):

- Decreased compressive strength approximately 20%.
- Decreased splitting tensile strength approximately 15%.
- Decreased flexural strength approximately 15%.
- Decreased modulus of elasticity approximately 45%.
- Increased water absorption approximately 50%.
- Increased drying shrinkage approximately 50%.
- Increased creep approximately 50%.

More recently, extensive experimental research has been carried out into the short-term deflection and ultimate load capacity and behaviour of RAC (Ajdukiewicz and Kliszczewicz, 2007; American Concrete Institute, 2004; Arezoumandi et al., 2015; Ignjatović et al., 2013; Maruyama et al., 2004; Sato et al., 2007). Although different types of recycled aggregate were used in these studies, the same conclusion was drawn. The results showed that RAC beams had a slightly lower moment capacity, reduced stiffness after cracking and higher deflection and higher levels of damage at failure in comparison to NC beams. Moreover, wider and more closely spaced cracks were observed in RAC beams than NC beams. Moreover, the shear behaviour of reinforced concrete members containing recycled concrete aggregate has also been investigated. The findings from some experimental studies (Arezoumandi et al., 2014; Michaud et al., 2016; Wardeh & Ghorbel, 2019) provided evidence that up to 30% coarse recycled concrete aggregate and 10% granular recycled aggregate may be incorporated into structural concrete mixtures without affecting the shear performance. More than this replacement percentage will make the shear strength of recycled aggregate concrete are lower than natural aggregate concrete.

To date, little attention has been given to the time-dependent behaviour of RAC beams under sustained loads. Lapko and Grygo (2010) tested beams made from NA and RCA under short-term and long-term loading. The long-term loading results showed a further 20% greater deflection and a 46% greater strain in the compression zone in the beams made with RCA. Knaack and Kurama (2015) studied the time-dependent sustained service-load behaviour of beams with normal and recycled concrete aggregate (RCA). Their findings revealed that an increase in the replacement ratio of recycled aggregate resulted in increased immediate and long-term deflections. They observed a similar increase in the number of cracks to that seen in the previous research mentioned above, which they attributed to the decrease in the modulus of rupture of RAC.

Using the ACI-318 (American Concrete Institute, 2004) and BS EN 1992-1-1: Eurocode 2 (British Standards Institution, 2004) prediction methods, the obtained estimations for the immediate deflections for NC beams were reasonable, however, the codes estimations were less accurate when it used to predict the long-term deflections of the cracked RAC beams; ACI-318 underestimated the deflections, whilst Eurocode 2 overestimated the deflections. In terms of the long-term deflections of the un-cracked RAC beams, the obtained results were significantly underestimated by both ACI-318 and Eurocode 2. In fact, these 'un-cracked' beams were only un-cracked initially, but cracked because of creep and shrinkage over time. Hence, treating these beams is very difficult using both codes if you do not take into account the change from State I to State II of the cracking behaviour.

On examination of the work presented by Knaack and Kurama, it appears that they have used the model of conventional concrete to predict the initial deflection without any modifications to include the effect of recycled aggregate. Due to this, it is difficult to make any assessment of the accuracy of the code prediction methods for long-term deflection. Knaack and Kurama, as well as Lapko and Grygo, did not attempt to explain the inaccuracies of the code prediction models or to provide any empirical modifications to the models to improve their accuracy.

Choi and Yun (2013) found the ratios between the long-term and immediate deflections for RAC beams made with coarse and fine CDW were smaller than the equivalent ratios for NC beams. They proposed a reduction factor, α ($\alpha = 0.92$ and 0.86 for recycled coarse and fine aggregate concrete, respectively) for modifying the modulus of rupture when predicting the short-term and long-term deflection of RAC beams using the ACI method. Modifying the tensile strength of the concrete is certainly an agreed way forward when calculating the crack spacing in a flexural element—the cracking theory proposed by Beeby (1990) clearly illustrates the relationship between tensile strength and crack spacing. It could also be argued that this approach is valid when considering the crack width calculation and the modification of this theory. However, in terms of deflection, rather than simply modifying the indirect tensile strength of the material, a more appropriate property to consider is the tension stiffening present in the section, as this not only represents the material, but also the composite interaction of the two elements (concrete and steel).

An attempt to represent the influence of this parameter on the deflection of NC is presented in Eurocode 2 (the β factor) and therefore allows easy modification when RAC beams are involved. In terms of crack width, Forth (Forth & Martin, 2014) highlighted the effect of tension stiffening (in the concrete between cracks) on the average strain in the steel in his comparison of the two formulae presented in Eurocode 2 (flexural) and Eurocode 2 Part 3 (axial); it is the average strain in the steel which is used to calculate the crack width in Eurocode 2. It therefore seems more reasonable that modifying the tension stiffening parameter is also a better approach to calculating crack width than simply modifying the tensile strength of the concrete.

Based on a review of the available literature (Choi & Yun, 2013; Knaack & Kurama, 2015; Łapko & Grygo, 2010), it is apparent that the guidance available in ACI-318 and Eurocode 2 is only really accurate when predicting the ultimate loads of RAC beams. When it comes to predicting the deflection (short and long-term) and cracking behaviour of RAC beams the codes require some slight modifications. This investigation concentrates on determining the effect of RAC on the tension stiffening property (as this is deemed to be the most representative parameter when considering deflections and cracking) and modifies the theory presented in Eurocode 2 by introducing this influence via the β factor.

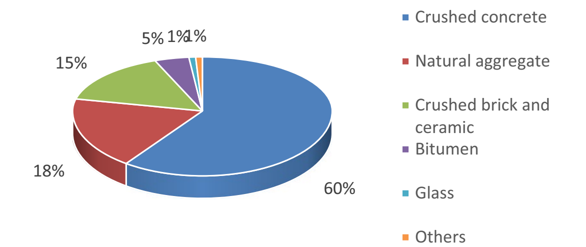

Fig. 1 Composition of the recycled aggregate used in this research

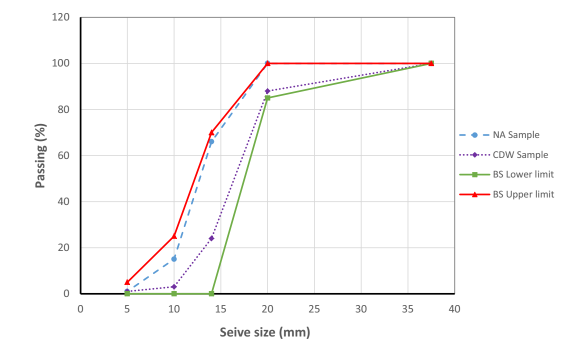

Fig. 2 Grading of the normal and recycled aggregate

3 Experimental Programme

3.1 Materials

Portland high strength cement (C52.5 N) was used for all mixes of this research. The cement is manufactured to meet the requirements of BS EN 197–1. According to the standard limits of BS EN 882, natural river sand was used as a fine aggregate (FA) with a maximum particle size of 5 mm. Two types of coarse aggregate were used: a natural coarse aggregate (NA) composed of un-crushed limestone with a maximum particle size of 20 mm (NA), and a recycled aggregate (RA) composed of crushed, washed construction and demolition waste (CDW) also with a maximum size of 20 mm. The composition of the CDW as provided by the supplier is presented in Fig. 1.

The grading and properties of both types of aggregate conformed to the standard requirements of BS EN 882 and BS EN 8500 as shown in Fig. 2 and Table 1. In terms of the grading, the main concern in this research was to ensure that the grading of the two types of aggregate fell between the maximum and minimum grading lines defined in BS EN 882 (see Fig. 2). By doing so any effects on creep due to the differences in grading would be minimised. In addition, the longitudinal and shear

Table 1 Properties of natural and recycled aggregate

Properties	Natural fine aggregate (FA)	Natural coarse aggregate (NA)	Recycled coarse aggregate (CDW)
Specific gravity	2.64	2.62	2.48
Bulk density (kg/m^3)	1580	1600	1360
Water absorption ratio (%)	1.06	0.89	4.78
Porosity (%)	-	38	46

reinforcement steel used in this research had a yield stress of 500 MPa and a modulus of elasticity of 200GPa.

3.2 Mix Proportions

Three different concrete mixes were designed and used for this research with three CDW replacement levels. The mixing water compensation method was followed in order to ensure all of the mixes had the same effective water-to-cement ratio (0.42). Additional water (AW) was added to the RAC mixes to compensate for the high-water absorption capacity of CDW (according to the final measured absorption ratio of CDW) and to achieve the required workability. The amount of additional water was calculated based on the amount of CDW in the mix and its water content. Details of the mix proportions and slump tests are summarised in Table 2.

3.3 Tension Stiffening Test

In the first stage of this research, six square-section prisms (120 × 120x1200 mm) reinforced with a central bar Ø16 mm were prepared and cast for the long-term tension stiffening tests as shown in Fig. 3. There were two specimens of each mix. The first specimen was subjected to a sustained load for 35 days (The test was stopped when the stabilisation in the trend of results occurred.), and the second specimen was stored next to the first one and was used to measure shrinkage. A special rig was built for this test in the George Earl Laboratory at the University of Leeds which is similar to that used by Scott and Beeby in 2005 (2005).

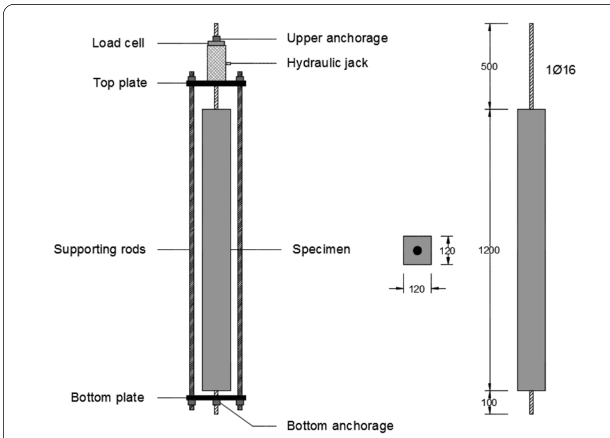

Fig. 3 Test rig for tension stiffening specimens

In the first specimen, three strain gauges were placed at 300-mm intervals along the length of the steel bar and were connected to a data logger to measure the strains in the bar over time. In addition, seven demountable mechanical strain gauges (DEMEC) were fixed on opposite sides of the concrete specimens every 150 mm in order to measure the surface strains of the concrete over time as shown in Fig. 4.

A direct tensile load of 45 kN was applied to the steel bar throughout the test using a hydraulic jack and load cell. The applied load corresponded to a stress of 200 MPa in the steel bar at the crack and matched the load applied during the beam test. The measured strains were used for calculating the reduction in tension stiffening of the concrete over time. Scott and Beeby's Method 1 was followed for the tension stiffening calculations; the details of this method are presented in Scott and Beeby (2005). The calculations of concrete tensile stresses were based on the following relationship:

$$\sigma_c = (F - F_s)/A_c \tag{1}$$

where σ_c is the concrete stress; F is the applied force; F_s is the force in the reinforcing bar; and A_c is the cross-sectional area of the concrete section. Method 1 required the assumption of strain compatibility between the steel and surrounding concrete. Average reinforcement

Table 2 Concrete mixes

Mix	Specimen	W/C	Mix proportions (kg/m^3) W	AW	C	FA	CA	CDW	Slump (mm)
M1	NC	0.42	177	0	422	754	1024	-	120
M2	RAC-50	0.42	177	8	422	754	512	512	125
M3	RAC-100	0.42	177	18	422	754	-	1024	135

W/C water cement ratio, *W* effective water, *AW* additional water, *C* cement, *FA* fine aggregate, *CA* coarse aggregate, *CDW* construction and demolition wastes

Fig. 4 Long-term tension stiffening test

stresses were then calculated over the sample length by assuming that average reinforcement strains were the same as the average surface strains computed from the hand-held mechanical strain gauge results. Calculation of average bar forces, and hence concrete stresses, was then straightforward. The final calculations were based on the loss of tensile stress in the concrete over time and the results were presented as a ratio between the measured long-term concrete stress and the initial stress which was measured directly after applying the load.

3.4 Beam Design and Test Procedures

In the second stage, full-scale beams were tested, long term, in flexure. All beams were prepared with the same longitudinal and shear reinforcement ratios using three different replacement levels of CDW (0%, 50% and 100%). All of the beams had a rectangular cross-section with a width of 300 mm and a height of 150 mm, and were 4.2 m in length, as shown in Fig. 5.

For the long-term tests, a stabilised cracking pattern was achieved in the simply supported beams by subjecting them to a sustained load of 23 KN (equivalent to a sustained moment of 17.2kNm (including the self-weight of the beam) and an average stress in the compression zone of around 7 MPa); the sustained load was maintained for a period of 90 days. The beam mid-span deflection was measured using LVDT and recorded by a data logger. Surface strain measurements were also taken at four different heights on both sides of the beams. DEMEC points were placed every 150 mm along the constant moment zone. Electrical resistance strain (ERS) gauges were placed on the top surface at the mid-span point of the three longitudinal reinforcing bars; these gauges were connected to a data logger and allowed automatic recording of the strains over the 90 days of the test. (The test was stopped when the stabilisation in the trend of results occurred.) The development of crack patterns and propagation were observed and marked on the beams; crack widths were measured using a hand-held optical microscope.

For each mix, six cubes (100 × 100x100 mm), four cylinders (150 × 300 mm), three prisms (100 × 100x500 mm) and four small prisms (75 × 75x200 mm) were prepared and cast. These specimens were tested to measure the compressive strength, splitting tensile strength, flexural strength, modulus of elasticity, creep and shrinkage of the resulting concrete. All of the beams and specimens were compacted immediately after casting and were left

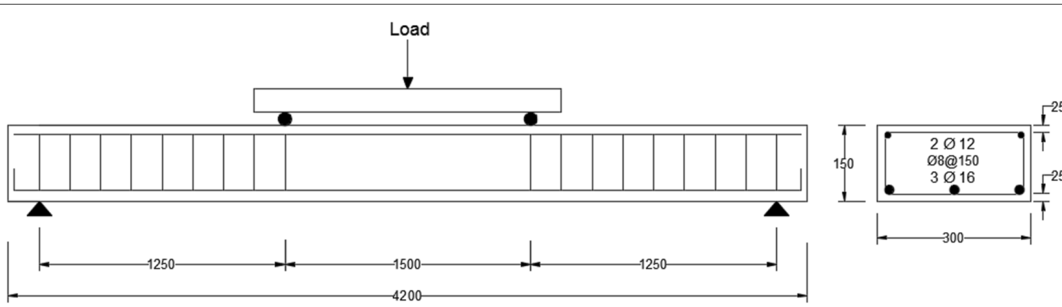

Fig. 5 Details of beam dimensions and reinforcement

Fig. 6 Test specimens and experimental set-up

Table 3 Mechanical properties of concrete

Specimen	f_{cu} (MPa)	f_c (MPa)	f_{spt} (MPa)	f_{ft} (MPa)	E_c (MPa)
NC	51.6	41.5	4.2	5.3	30,600
RAC-50	49.2	39.0	3.7	4.8	25,200
RAC-100	47.3	37.4	3.2	4.3	22,500

f_{cu} cubic compressive strength, f_c cylindrical compressive strength, f_{spt} splitting tensile strength, f_{ft} flexural strength, E_c modulus of elasticity

for 24 h before being removed from their moulds and transferred to the curing room for 28 days. Fig. 6 shows the test specimens and experimental set-up.

4 Results and Discussion

4.1 Mechanical Properties

The measured mechanical properties of the concrete are summarised in Table 3. It is evident that due to the incorporation of CDW as RA, there was a reduction in all of the mechanical properties. In comparison with normal concrete, the results showed a reduction of 5 and 10% in the compressive strength, 15 and 30% in the splitting tensile strength, 10 and 22% in the flexural strength and 20 and 36% in the modulus of elasticity when 50 and 100%, respectively of the natural aggregate was replaced. As reported in the literature, these reductions are mainly attributed to the poor quality of the recycled aggregate. This poor quality is mainly due to the presence of old cement paste and other materials such as clay bricks and tiles (Brito & Saikia, 2012; Etxeberria et al., 2007; Juan & Gutiérrez, 2009; Kishore, 2007; Kosior-Kazberuk & Grzywa, 2014; Maleševet al., 2010; Rahal, 2007; Sryh & Forth, 2015; Xiao et al., 2005; Yang et al., 2008).

4.2 Short-Term Deflection and Cracking Behaviour

Fig. 7 shows the relationship between the applied load and short-term, mid-span deflection of the beams. The measurements were taken up to an applied load of 23 KN (the value of the sustained load). The results indicate that the overall load–deflection behaviour of the RAC beam was similar to the behaviour of the conventional concrete beam (NC). The maximum mid-span deflection increased by about 8 and 15% when 50 and 100% of CDW was added, respectively. For the two replacement levels (50 and 100%), the initial cracking loads measured for the beams containing recycled aggregate were about 15 and 30%, respectively less than that recorded in the normal concrete beams.

In terms of cracking, the RAC beams showed different cracking patterns to the NC beams. Wider and more closely spaced cracks were observed in the RAC specimens as detailed in Table 4 and Fig. 8. The results of this study were, therefore, similar to those reported earlier

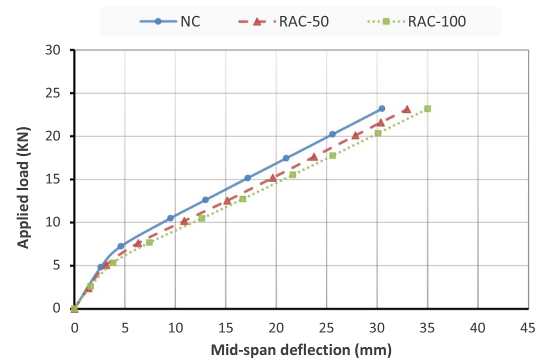

Fig. 7 Short-term deflection

Table 4 Details of cracks during stabilised cracking stage

Specimen	Number of cracks	Space between cracks (mm)	Crack width (mm)	
			t_0	t_{90}
NC	16	110	0.10	0.16
RAC-50	18	90	0.16	0.24
RAC-100	20	70	0.20	0.30

* The results are the average of the readings of both sides

t_0 = time at start of loading (age of 28 days), t_{90} = time at 90 days of loading (age of 118 days)

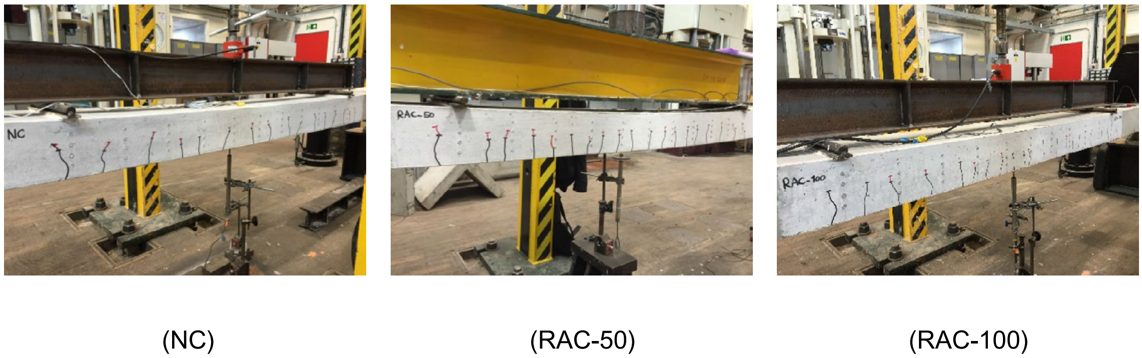

Fig. 8 Cracking patterns of the tested beams

from previous investigations (Ajdukiewicz and Kliszczewicz, 2007; American Concrete Institute, 2004; Ignjatović et al., 2013; Maruyama et al., 2004; Sato et al., 2007). A reduced crack spacing and hence a greater number of cracks can clearly be linked to the lower tension stiffening and tensile strength of the RAC; as can the lower initial cracking loads which all can make the defection to be higher.

4.3 Creep and Shrinkage

Creep and shrinkage significantly affect the long-term deformations of concrete structures. As mentioned before, one of the main problems with using recycled aggregate is their low properties and high porosity, which is the result of the presence of old cement paste and other materials such as clay bricks and tiles. The old cement paste which adheres to the natural particles and the presence of bricks and tiles particles can decrease the volume of the aggregate in the mixture and increase the water content which leads to increased creep and shrinkage. In addition, the lower elastic properties of recycled aggregate can significantly influence the results of creep and shrinkage.

In this research, four small prism samples (75 × 75x200mm) were tested to assess the effect of RA on the compressive creep and shrinkage strains. Specimens were stored in a controlled environment at 20 °C and a relative humidity of 45%, similar to the average temperature and humidity in the laboratory where the beams were tested.

For the compressive creep test, the specimens were subjected to a constant compressive stress of 10 MPa (which is equivalent to $0.2f'_c$ of the control specimen). The compressive creep strains and coefficients were calculated based on the average results from the two specimens after removing the elastic strain and taking into account shrinkage. The creep and shrinkage data are presented in Fig. 9, the curves of the test results showed that

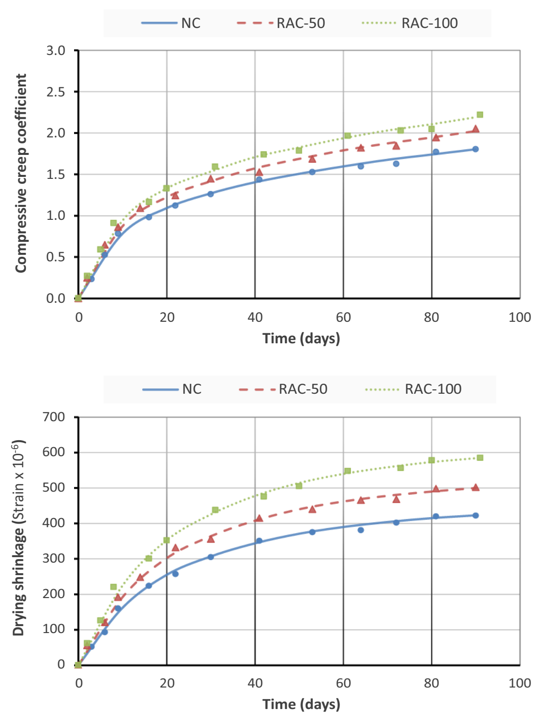

Fig. 9 Results of creep and shrinkage

the compressive creep coefficient and the shrinkage of the RAC increased by about 15 and 30%, and 18 and 38%, respectively, as a result of incorporating 50 and 100% recycled aggregate. These increases reflect the importance of understanding the long-term behaviour of RAC members.

4.4 Long-Term Loss of Tension Stiffening

Fig. 10 illustrates the effect of using CDW on the long-term loss of tension stiffening. The reduction over time of the ratio between the long-term concrete stress and the initial concrete stress was used to represent the loss

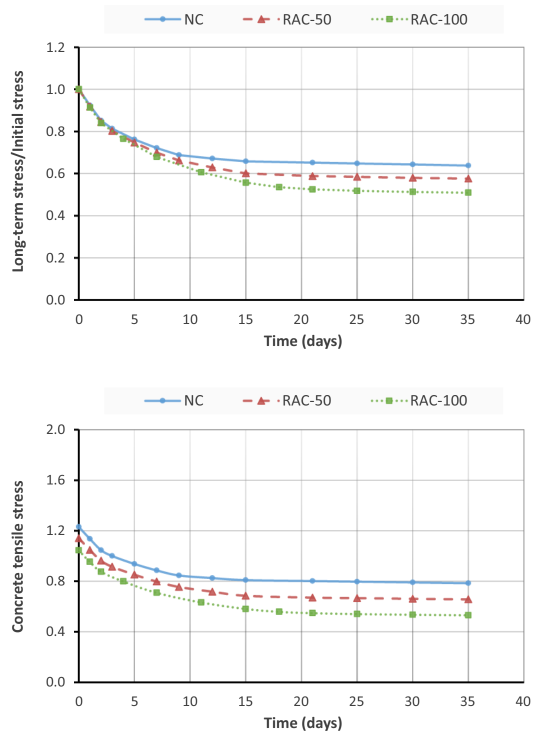

Fig. 10 Effect of recycled aggregate on the long-term loss of tension stiffening

of tension stiffening. The figure also shows the loss in the actual concrete tensile stress as a function of time for the NC and RAC specimens. As can be seen from the figure, there is a very rapid loss of tension stiffening in all of the specimens during the early stage of the test. Up until day 5, the normal concrete specimen and recycled aggregate concrete specimens exhibit similar reductions of around 25% from the initial applied stress. After day 5, the recycled aggregate specimens showed a higher rate of loss of tension stiffening in comparison to the normal concrete specimen.

The figure also shows that the stress in the normal concrete specimen stabilised earlier than that in the RAC specimens which only occurred at the 20th and 25th days for the 50 and 100% samples, respectively. After stabilisation occurred, the rate of loss of tension stiffening remained constant for all of the specimens. On the final day of testing (35th day), the tensile stress in the normal concrete had reduced by 36.2% while the stress in the RAC specimens had reduced by 42.4 and 49.1% for the 50 and 100% recycled aggregate specimens, respectively. This means that by substituting 50 and 100% of the aggregate, the loss of tension stiffening increased by 6.2 and 12.9%, respectively. Table 5 summarises the average short and long-term tensile stresses for the NC and RAC specimens.

Table 5 Experimental results for concrete tensile stresses

Specimen	Short-term stress (MPa)	Long-term stress (MPa)	Ratio (%)
NC	1.23	0.785	63.8
RAC-50	1.14	0.656	57.6
RAC-100	1.04	0.531	50.9

In general, it can be concluded that the higher the replacement percentage of CDW, the greater the loss of tension stiffening. This can be attributed to the effect of the inclusion of the CDW as recycled aggregate on the mechanical properties of the concrete, in particular the tensile strength which is the most significant factor affecting tension stiffening. Furthermore, the effect of recycled aggregate on the microstructure of the Interfacial Transition Zone (ITZ) can influence the microcracking of the concrete matrix under load which can also cause the observed reduction in tension stiffening as discussed earlier in the section regarding the results of the mechanical properties.

4.5 Long-Term Flexural Behaviour

Fig. 11 shows a graph of the long-term mid-span deflection versus time for all of the tested beams. In general, the specimens all showed a similar trend in deflection over the period of time, i.e. the deflection increased continuously. It is clear from the results that the increase in long-term deflection was much more rapid during the first 20 days of loading. The majority of the long-term deflection (about 65%) occurred during this time. Furthermore, the results indicate that increasing the replacement ratio of CDW resulted in significant increases in long-term deflection. The long-term deflection increased

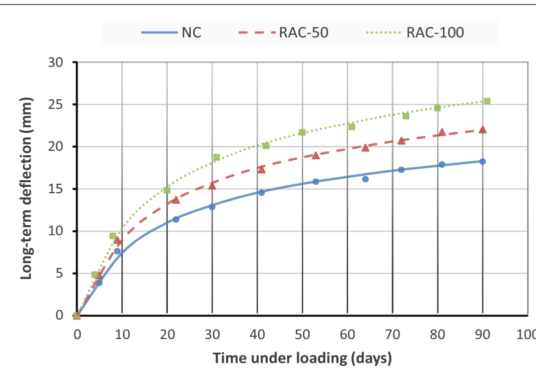

Fig. 11 Long-term deflection

by 20 and 38% as a result of replacing 50 and 100% of the aggregate, respectively. This was attributed to the effect of recycled aggregate on the properties of the concrete, in particular the time-dependent deformation (e.g. creep and shrinkage).

In terms of crack development, the cracks in the RAC beams extended further throughout the height of the section than those in the NC beams as shown in Fig. 8. Also, the cracks were wider in the RAC beams under sustained load, as summarised in Table 4, which agrees with the observations of Choi and Yun (Choi & Yun, 2013). It can be noticed from the results that the percentage of the increase in the crack width decreased by increasing the replacement ratio. This can be owed to the increased number of cracks with increasing the replacement ratio of CDW which reduced the spaces between the cracks and hence distributed the development of width on more cracks.

5 Analytical Investigation

Based on the CEB-FIB Model Code, the BS EN 1992-1-1: Eurocode 2 (EC2) approach was proposed to estimate the deformations (curvature, strain, deflection, etc.) of beams subjected to bending (British Standards Institution, 2004). Expression 7.18 of Eurocode 2 is used to determine the deformation parameter, α, as shown below:

$$\alpha = \xi\alpha_{II} + (1 - \xi)\alpha_I \tag{2}$$

where α_I and α_{II} are the values of the deformation parameters calculated for the un-cracked and fully cracked stages, respectively, and ξ is the distribution coefficient that is used to model the effects of the tension stiffening of the section. ξ is calculated from Expression 7.19 of Eurocode 2 as follows:

$$\xi = 1 - \beta(M_{cr}/M_a)^2 \tag{3}$$

where β is a coefficient which takes into account the influence of the duration and type of loading ($\beta = 1$ for short-term loading and 0.5 for long-term or repeated loading). M_{cr} is the first cracking moment and M_a is the applied moment.

Eurocode 2 is used to predict the long-term curvature of a beam in bending and includes the effect of creep and shrinkage separately. The effect of creep is included by modifying the modulus of elasticity of the concrete through the Effective Modulus Method (EMM) based on the creep coefficient as shown below:

$$E_{cef}(t_0, t) = \frac{E_{c0}}{1 + \varphi_c(t_0, t)} \tag{4}$$

$$\frac{1}{r_c} = \xi\frac{M_a}{E_{cef}I_c} + (1 - \xi)\frac{M_a}{E_{cef}I_u} \tag{5}$$

whereas the curvature due to the shrinkage effect is calculated using:

$$\frac{1}{r_{sh}} = \xi\varepsilon_{sh}\alpha_e\frac{S_c}{I_c} + (1 - \xi)\varepsilon_{sh}\alpha_e\frac{S_u}{I_u} \tag{6}$$

where ε_{sh} is the shrinkage strain, α_e is the modular ratio, S_c and S_u are the first moments of area of the reinforcement about the centroid of the cracked and un-cracked sections and I_c and I_u are the second moments of area of the cracked and un-cracked sections.

The total long-term curvature is calculated using the expression:

$$\frac{1}{r} = \frac{1}{r_c} + \frac{1}{r_{sh}} \tag{7}$$

and the total long-term deflection is:

$$\Delta = KL^2\frac{1}{r} \tag{8}$$

where K is the deflection coefficient factor which depends on the loading case and bending moment diagram and L is the span of the member.

By following the equations of Eurocode 2 and using the experimental results for the concrete strength properties, creep and shrinkage, the predictions for the 90-day (total long-term deflections) were calculated and are summarised in Table 6. The code predictions showed good agreement with the experimental results for the normal concrete beams. However, it can be seen that when the replacement ratio of recycled aggregate increased, the predictions using the Eurocode 2 method are less accurate and underestimate the short-term and long-term experimental values. (Note: due to the loading system applied to the beams of this investigation and the subsequent size of the constant moment zone and the fact that a stabilised crack pattern was produced within the constant moment zone a constant distribution coefficient, based on the maximum moment in the span, was utilised within the code method for predicting curvature/deflection. Potentially, this could have been conservative, over-predicting the deflection. However, as can be seen from Fig. 12 (NC), this approach did appear to be appropriate).

Table 6 Experimental values of beam deflection

Specimen	Short-term deflection (mm)		Long-term deflection (mm)	
	EXP	EC2	EXP	EC2
NC	30.49	29.73	18.30	18.23
RAC-50	32.97	31.41	21.99	20.19
RAC-100	35.00	32.93	25.36	23.35

This underestimation by the code is due to the tension stiffening behaviour of the RAC beam as compared to the NC beam (as discussed in Sect. 4.4) which is not taken into account in the code method for prediction the deflection. At 90 days, the code predictions are still within 10% of the measured values, however, by comparing the trends of the measured and predicted curves, the error at ultimate will be greater and exceed the normally acceptable ± 20% error for these type of predictions (Narayanan and Beeby) (Narayanan & Beeby, 2005).

More specifically, the Eurocode 2 approach incorporates the effect of the loss of tension stiffening using a fixed value for the factor β ($\beta = 1$ for short-term loading and 0.5 for long-term or repeated loading) which does not vary for different types of concrete. Therefore, based on the experimental results of the long-term tension stiffening tests and the recommendations of Whittle and Jonse (Whittle & Jones, 2004) and Scott and Beeby (Scott & Beeby, 2012) in order to account for the effect of tension stiffening on the flexural behaviour, modifications are proposed to the Eurocode 2 method to address the effect of the addition of RA. The results indicate that with an increase in the level of RA, the value of β should reduce to below 0.5 for calculating long-term deflections. According to these results, β values of 0.4 and 0.3 are proposed for concrete with 50 and 100% of RA replacement, respectively. These values were obtained from a back-calculation of the long-term experimental deflections.

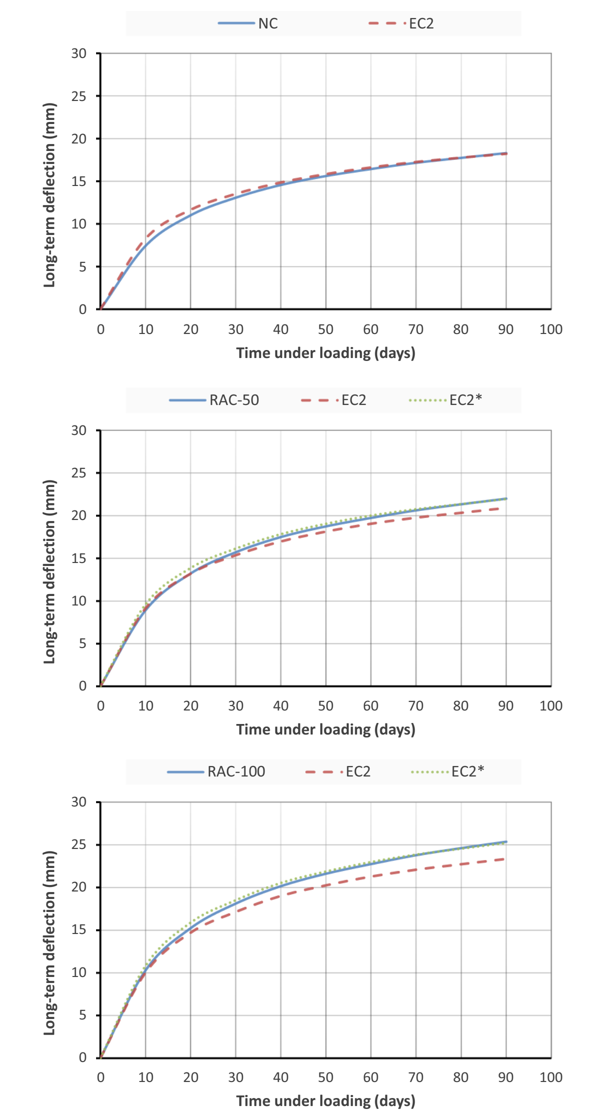

Fig. 12 Comparison of the experimental and predicted long-term deflection results of tested beams

Another statistical method for extrapolating this type of hyperbolic results which was suggested by Ross (Ross, 1937) and recommended by Neville et al. (1983), was also used as shown below:

$$\Delta(t, t_0) = \frac{(t - t_0)}{\mathrm{A} + \mathrm{B}^*(t - t_0)} \tag{9}$$

where $\Delta(t, t_0)$ = the deflection at anytime; $(t - t_0)$ = time under loading (days); and A and B = constants.

When $(t - t_0)$ reaches infinity, the ultimate deflection will be 1/B. Hence, the limiting deflection can be found from the experimental results that have been obtained by plotting the relationship between $[(t - t_0)/\Delta(t, t_0)]$ and $(t - t_0)$ for each case. The slope of this linear relationship represents the constant B, and the intercept of the ordinate is the constant A. Fig. 13 shows the hyperbolic relations proposed by Ross (1937) for extrapolating the results of (RAC-100).

Using only the 90-day data to produce the revised values of beta was assessed by extrapolating the data beyond 90 days for 25 years using the Ross hyberbola and calculating the ultimate deflection (long-term tests are

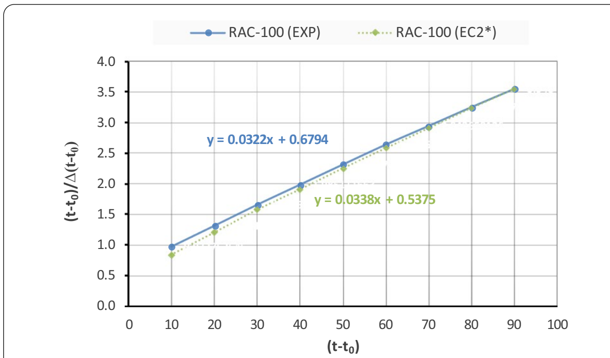

Fig. 13 Hyperbolic relations proposed by Ross for extrapolating the results of (RAC-100)

normally performed for at least 6 months or to a point when the curve has flattened out a lot more). The error between the extrapolated long-term deflections (experimental and code predictions) after 25 years of loading did not exceed 5%, hence confirming our use of the 90-day beam data.

The application of these proposed values of beta from the long-term deflection calculations gave more accurate predictions when the experimental results of the short-term deflections were used as shown in Fig. 12. The proposed calculation method was validated using results from previous experimental investigations presented in the literature. The results from this research and from the data of Lapko and Grygo (2010) and Knaack and Kurama (2015) are presented in Table 7. The comparison between the experimental and predicted results confirms that the modification provides more accurate results.

6 Conclusions

In this research, the effect of recycled aggregate on the long-term flexural behaviour of reinforced concrete beams was investigated. The following conclusions can be drawn from this investigation:

- In terms of ultimate and serviceability limit state performance, this investigation further confirms the potential for the use of recycled aggregate in structural concrete mixes. However, further research is required to assess the durability of RAC and its interaction with structural performance.
- Modifying the tension stiffening parameter present in the Eurocode 2 method for predicting deflection appears to be a suitable approach to accommodating the effect of recycled aggregate on the long-term performance of RAC. (The approach needs to be further extended to assess its suitability with respect to modifying the Code approach to predicting crack spacing and width.)
- There was a noticeable increase in the long-term deflection of the RAC beams which reflects the effect of recycled aggregate on the creep and shrinkage, as well as on the long-term loss of tension stiffening; all of which are the main parameters that constitute long-term deflection.
- Recycled aggregate reduces the mechanical properties of concrete and also the first cracking moment of RAC beams. Increasing the proportion of recycled aggregate results in higher short-term deflections and wider and closer cracks.
- The accuracy of the Eurocode 2 predictions for long-term deflections of reinforced concrete beams observed in this investigation and the ease with which it can be modified, confirm the appropriateness of this method for design purposes.

Table 7 Comparison between experimental results and predictions from the proposed analytical approach

Study	Specimen	Long-term deflection (mm)		
		EXP	EC2	EC2*
This research	NC	18.30	18.23	18.23
	RAC-50	21.99	20.19	22.10
	RAC-100	25.36	23.35	25.37
Lapko and Grygo (Łapko & Grygo, 2010)	N-LT	14.00	12.54	14.19
	R-LT	16.00	14.86	15.78
Knaack and Kurama (Knaack & Kurama, 2015)	CC-0-28	10.19	10.08	10.08
	CC-50-28	11.22	10.58	11.03
	CC-100-28	12.27	11.32	12.26

Acknowledgements
The authors express their sincere gratitude to the sponsors of this research: The Libyan Embassy in the UK and the School of Civil Engineering at the University of Leeds.

Authors' contributions
LS and JF conceived of the presented idea. LS and JF designed and planned the experiments. LS carried out the experimental programme. JF encouraged LS to investigate the long-term loss of tension stiffening and supervised the findings of this work. LS performed the analytical investigation and performed the numerical calculations. Both LS and JF authors discussed the results and proposed the computational adjustment. LS took the lead in writing the manuscript and JF provided critical feedback and helped shape the final manuscript. All the authors read and approved the final manuscript.

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Funding
The authors declare that they have not received any fund for this project.

Availability of data and materials
All data generated or analysed during this study are included in this published article. Any more datasets are available from the corresponding author on reasonable request.

Declarations

Competing interests
The authors declare that they have no competing interests.

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Received: 12 May 2021 Accepted: 22 February 2022
Published online: 12 April 2022

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