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Creep behaviour of concrete using recycled coarse aggregates obtained from source concrete with different strengths

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HIGHLIGHTS

- Influence of strength of source concrete on creep of RAC.
- Different increase in creep induced by RCA for RAC with different w/c ratios.
- Model to predict the creep deformation of RAC.

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ABSTRACT

Available creep models for recycled aggregate concrete (RAC) only consider the effect of residual mortar content (C_{RM}). This paper highlighted how the creep of RAC was also influenced by the property of the residual mortar which highly depended on the water-to-cement ratio of the source concrete (w_{or}/c_{or}) and how the increase in creep which was induced by the recycled coarse aggregate (RCA) varied with the water-to-cement ratio of the resulting concrete (w/c). Forty RAC specimens with the w_{or}/c_{or} ratios and the w/c ratios varying between 0.3 and 0.6 were prepared and tested up to 8 months. It was found that the influence of the RCA on the creep deformation of RAC was more pronounced for RAC with lower value of w/c or using RCA from source concrete with higher w_{or}/c_{or} ratio. Finally, a 'water-to-cement ratio factor' was introduced to the available creep model to account for these influences. Benchmarking analysis against available experimental data indicated that, the newly proposed model had better accuracy in predicting creep of RAC, especially for RAC with aggregates obtained from high-strength concrete.

1. Introduction

Using recycled aggregates crushed from demolished concrete to produce new concrete can reduce the consumption of natural sources and save the landfill spaces. This kind of sustainable material is commonly referred to as recycled aggregate concrete (RAC). The RAC is originally studied for non-structural application which is usually characterized by its low compressive strength (e.g. [1–3]). In recent years, extensive research efforts have been devoted to extend the application of RAC for structural use (e.g. [4–6]). Tremendous achievements have been made on the short-term mechanical behaviour of structural RAC (e.g. [7–9]). Research efforts have also been focusing on the durability performance of structural RAC, such as the carbonization, the chloride penetration, the freeze-and-thaw resistance and the shrinkage etc. (e.g. [10–16]). Compared to the mechanical behaviours mentioned above, the creep behaviour of structural RAC has not drawn enough research attention despite the fact that creep resistance is one of the key issues that need to be accounted in the service design for structures.

Ravindrarajah and Tam [17] reported one of the earliest experimental investigations on the creep of RAC. In this research, all the RAC had the natural aggregates 100% replaced by the recycled ones. Following their work, Nishibayashi and Yamura [18] measured the specific creep for RAC with different water-to-cement ratios. All the tested RAC still have particular recycled coarse aggregate replacement ratio (r) of 100%. More than ten years later, Limbachiya et al. [19], Kou et al. [20] and Manzi et al. [6] tested the shrinkage and creep behaviour of RAC with higher strength (50 MPa or greater) and with the aggregate replacement ratios varying between 0% and 100%. Gómez-Soberón [21]

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Abbreviations

COV	coefficient of variation
L.O.I	loss on ignition
NA	natural aggregate
NAC	natural aggregate concrete
NCA	natural coarse aggregate
RAC	recycled coarse aggregate concrete
RCA	recycled coarse aggregate
SSD	saturated-surface-dry condition for recycled coarse aggregates
a	edge size of the specimen at the cross-section, mm
C_{RM}	residual mortar content, which is the ratio of the oven-dry weight of residual mortar over the oven-dry weight of RCA, $C_{RM} = W_{RM}^{RAC}/W_{RCA}^{RAC}$
$C(t,t_0)$	specific creep, which represents the creep deformation at time t for concrete specimens subjected to unit stress first applied at time t_0, με/MPa
D_A	density of the aggregate at SSD condition, kg/m^3
D_{OVA}	density of the original virgin aggregate in RCA, kg/m^3
D_{RCA}	density of the recycled aggregate at SSD condition, kg/m^3
D_{RM}	density of the residual mortar in RCA at SSD condition, kg/m^3
E_{c28}	elastic modulus of concrete at 28 days, MPa
E_{NAC}, E_{RAC}	elastic modulus of NAC and RAC, respectively, MPa
E_{NA}	elastic modulus of natural coarse aggregate, MPa
f	passing percentage using the square mesh with a dimension of 80 μm
$f_{c,3}$, $f_{c,28}$	compressive strength of cement at 3 days and 28 days, respectively, MPa
$f_{ct,f,3}$, $f_{ct,f,28}$	flexural tensile strength of cement at 3 days and 28 days, respectively, MPa
f_{cm28}	cylinder compressive strength of concrete at 28 days, MPa
$f_{cm}(t)$	cylinder compressive strength of concrete at time t, MPa
$f_{cu,100}$	28-day compressive strengths of concrete obtained from the 100 × 100 × 100 mm cube tests, MPa
f_{cu}	28-day cubic compressive strength of the resulting concrete obtained from the 150 × 150 × 150 mm cube tests, MPa
$f_{cu(or)}$	28-day cubic compressive strength of the source concrete used to produce RCA, MPa
f_{cuk}	28-day characteristic cubic compressive strengths of concrete, MPa
h	height of the specimen, mm
K_{RCA}	amplification factor on creep deformation induced by the incorporation of recycled coarse aggregates
K_{RC}	recoverable creep coefficient in creep model, which can be determined with Eq. (23) or Eq. (24)
$k_{w/c}$	w/c ratio factor in creep model, which can be determined with Eq. (20)
n_c	sustained stress level in concrete
N_L	sustained axial force on specimens, kN
r	replacement ratio of RCA
RH	relative humidity
t_0	concrete age at first loading
V_{CA}^{NAC}	total volume fraction of natural coarse aggregate in NAC
V_{CA}^{RAC}	total volume fraction of coarse aggregate in RAC, $V_{CA}^{RAC} = V_{NCA}^{RAC} + V_{RCA}^{RAC}$
V_{NCA}^{RAC}, V_{RCA}^{RAC}	volume fraction of new NCA and RCA in RAC, respectively, $V_{RCA}^{RAC} = V_{OVA}^{RAC} + V_{RM}^{RAC}$
V_{NM}^{RAC}, V_{RM}^{RAC}	volume fraction of new mortar and the residual mortar in RAC, respectively
V_{OVA}^{RAC}	volume fraction of the original virgin coarse aggregate contained in RCA for RAC
V_{TNCA}^{RAC}	total volume fraction of natural coarse aggregate in RAC
W	water content in unit volume of concrete
W_{CA}^{RAC}	weight of coarse aggregate in unit volume of RAC
W_{OVA}^{RAC}	weight of original virgin coarse aggregate content contained in RCA particles for unit volume of RAC
W_{RCA}^{RAC}	weight of the RCA in unit volume of RAC, $W_{RCA}^{RAC} = W_{OVA}^{RAC} + W_{RM}^{RAC}$
W_{RM}^{RAC}	weight of residual mortar contained in RCA particles for unit volume of RAC
w/c	effective water-to-cement ratio of the resulting concrete
w_{or}/c_{or}	water-to-cement ratio of the source concrete used to produce RCA
$\varepsilon_c(t)$	creep strain of the concrete specimen at time t
ϕ_{RAC}, ϕ_{NAC}	creep coefficient (i.e. the ratio of the creep strain over the instantaneous one) at the end of long-term test for RAC and NAC, respectively
μ_{NAC}, μ_{RAC}	Poisson's ratio of NAC and RAC, respectively
μ_{NA}, μ_{RCA}	Poisson's ratio of NA and RCA, respectively
ω	water absorption of the aggregates

experimentally investigated the basic creep behaviour of the RAC with the aggregate replacement ratio (r) of 0%, 15%, 30%, 60% and 100%. Ajdukiewicz and Kliszczewicz [22] have focused on the long-term responses of RAC with the recycled aggregates obtained from high-strength concrete. Domingo-Cabo et al. [23] experimentally compared the creep and shrinkage behaviour of RAC and the natural aggregate concrete (NAC) with the same total water-to-cement ratio. In all the experiments mentioned above, the aggregate replacement ratio (r) is considered as the key factor that influences the creep behaviour of RAC. It has been commonly accepted that the attached old mortar around stone particles of the recycled aggregate increases the creep deformation for RAC. In this context, RAC with higher value of r ratio, which contains more old mortar, will have higher creep deformation. But the r ratio cannot be used as the sole factor to evaluate the creep deformation of RAC, as the increase of creep in comparison with the companion NAC can vary between 30% and 75% for RAC reported in different papers with the same aggregate replacement ratio. This is mainly because the qualities of the recycled aggregates from different sources can be quite different, which plays a vital role on the concrete's creep performance.

Some researchers have highlighted that it is actually the amount of the adhered old mortar in concrete mix instead of the aggregate replacement ratio that determines the creep response of RAC (e.g. [24–27]). Some researchers also experimentally investigated the variation of creep deformation for RAC with the water-to-cement ratios [28–30], the aggregate-to-cement ratios [30], and different sources of concrete [31]. But, still, these cannot explain the fact that some tested RAC specimens even exhibited better creep performance than the reference NAC (Manzi et al. [6], Ajdukiewicz and Kliszczewicz [22]).

From the authors' point of view, the influence of the incorporation of RCA on the creep of the resulting concrete depends not only on the amount of the adhered old mortar but also on the property of the parent concrete and that of the resulting concrete. Actually, based on a careful observation from some reported long-term experiments, the authors have already found that RAC specimens with different water-to-cement ratios (w/c) and with RCAs from