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Creep and drying shrinkage characteristics of concrete produced with coarse recycled concrete aggregate

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ABSTRACT

Laboratory tests are performed to investigate the effects of a new method of mixture proportioning on the creep and shrinkage characteristics of concrete made with recycled concrete aggregate (RCA). In this method, RCA is treated as a two component composite material consisting of residual mortar and natural aggregate; accordingly, when proportioning the concrete mixture, the relative amount and properties of each component are individually considered. The test variables include the mixture proportioning method, and the aggregate type. The results show that the amounts of creep and shrinkage in concretes made with coarse RCA, and proportioned by the new method, are comparable to, or even lower than, those in similar concretes made entirely with natural aggregates. Furthermore, it is demonstrated that by applying the proposed "residual mortar factor" to the existing ACI and CEB methods for calculating creep or shrinkage of conventional concrete, these methods could be also applied to predict the creep and shrinkage of RCA-concrete.

1. Introduction

Concrete structures usually last for several decades, yet sometimes their demolition is unavoidable for reasons such as structural/material deterioration, natural disasters, and war-inflicted damages. The global concrete and masonry rubble production is estimated to be one billion tons per year [1], but only a small fraction of this waste is used in the construction of new structures, especially as recycled concrete aggregate (RCA) in new concrete, despite the environmental and even economic benefits of recycling [2]. This can be attributed to the paucity of technical data, specifications, quality control and quality assurance procedures for making and using concrete made with RCA. There is also a perception that RCA is inherently a lower quality material compared to natural aggregate and is therefore unsuitable for use in structural grade concrete. The perception is supported by the results of some studies which have shown concrete made with RCA, termed RCA-concrete, to have lower elastic modulus [3–9] and higher creep and shrinkage [3,8,10–16] than similar NA-concrete, i.e., concrete containing only virgin natural aggregate (NA).

The writers have postulated that the lower elastic modulus and higher creep and shrinkage properties of RCA-concrete, as reported by some researchers, are due to the difference in the proportions of the ingredients of RCA-concretes vis-à-vis their companion NA-concretes rather than the properties of RCA per se [17]. The RCA-concretes in these studies were proportioned using the mixture proportioning methods for NA-concrete [18], which essentially treat RCA as another homogeneous aggregate similar to natural aggregate. In these methods, to proportion RCA-concrete, the natural aggregate in a reference NA-concrete is totally or partially replaced by an equivalent weight or volume of RCA. The two types of aggregate are normally distinguished by the difference between their absorption properties and densities. Due to the presence of the residual mortar in RCA, this direct replacement of natural aggregate by RCA in fact reduces the natural aggregate content and increases the total mortar (fresh plus residual mortar) content of the RCA-concrete vis-à-vis the reference NA-concrete. It is hypothesized here that the excess mortar and lower natural aggregate content of RCA-concretes proportioned by conventional methods are primarily responsible for their reported lower elastic modulus and higher creep and shrinkage. Note that research has shown [10,19,20] that RCA-concrete of high strength can be produced using conventional mix proportioning methods, but these

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seemingly inconsistent results can be explained by the fact that the compressive strength of concrete is primarily dependant on the strength of its two components (aggregate and mortar) and on the quality of the aggregate-mortar interfacial transition zone while the elastic modulus, creep and shrinkage are greatly influenced by the volume fraction and the elastic modulus of the aggregates [21]. Since it is not a given that in every case the residual mortar and natural aggregate in RCA would have lower strength than the companion fresh mortar and new natural aggregate in a RCA-concrete mixture, it is possible to achieve RCA-concrete mixes with compressive strength comparable to NA-concrete. On the other hand, using conventional concrete mixture design methods to proportion RCA-concrete mixes will always lead to excess mortar and lower natural aggregate volume in the latter mixes, consequently, to higher creep and shrinkage and lower elastic modulus in RAC-concrete mixes compared to companion NA-concrete mixes.

To check the validity of the preceding hypothesis, in this investigation the creep and shrinkage behaviors of RCA-concrete mixes proportioned by the conventional method and by a new method developed by the writers are compared with the corresponding behavior of similar NA-concrete mixes. The new method is dubbed the *Equivalent Mortar Volume* (*EMV)* method, and its complete details are given by Fathifazl et al. [22]. However, for clarity and completeness, it is briefly recapped below.

It should be stated in the outset that until now the EMV method has been applied to concrete mixes containing only coarse RCA and in the present discussion, unless stated otherwise, the term aggregate refers to coarse aggregate only. In this method first a reference NA-concrete mix, with specified properties and using virgin natural aggregate similar to the natural aggregate in RCA, is designed using conventional mixture proportioning methods as specified by ACI [18]. The mix is then modified by partially replacing the natural aggregate by RCA. In the EMV method, RCA is treated as a two component composite material, consisting of residual mortar and natural aggregate. The volume fractions of these components can be determined using the procedure described by Abass et al. [23]. Based on the determined volume fractions, the fresh mortar and virgin aggregate proportions of the reference mix are adjusted such that the total mortar and total natural aggregate volumes in the RCA mix and the reference mix become equal. Note again that aggregate here refers to coarse aggregate only. This normally requires reduction of the fresh mortar content of RCA mix and addition of an equivalent volume of virgin coarse aggregate to the mix. The adjusted quantities of fresh mortar and natural aggregate volumes will be function of the volume fraction of the residual mortar in RCA. The final outcome of this process is an RCA-concrete mix that has the same volume of total mortar and natural aggregate as the reference NA-concrete, the main difference between the two is that the total mortar in NA-concrete is all fresh mortar while in the RCA-concrete it is a combination of fresh and residual mortar. Similarly, in the RCA-concrete, the total aggregate is composed of fresh natural aggregate and the natural aggregate contained in RCA.

Using this method, Fathifazl et al. [22] have demonstrated that high quality and durable [24] RCA-concrete with consistent strength and elastic modulus can be produced. Tests on reinforced concrete beams under flexure and shear have shown that RCA-concrete members proportioned by the EMV method have equal or higher compressive, flexural and shear strength than the reference concrete beams [22,25–26].

The main objectives of this study are to experimentally study the creep and shrinkage properties of concrete mixes made with coarse RCA and proportioned by the EMV method and to investigate whether they experience similar creep and shrinkage as reference concrete mixes. Furthermore, the study's aim is to examine the applicability of the existing empirical equations for predicting creep and shrinkage of NA-concrete to RCA-concrete.

2. Experimental investigation

The variables studied in this investigation are the concrete mix proportioning method, the RCA source, and the aggregate type. Two different sources of RCA were used in the study, and are designated as RCA-M and RCA-V, obtained from demolition concrete recycling plants in Montreal (M) and Vancouver (V), respectively. The natural aggregate in RCA-M was limestone while that in RCA-V was river-bed gravel. It is not known whether either RCA used in this study came from single or multiple demolition projects.

2.1. Concrete mixes ingredients

All the concrete mixes were made using Type I Portland cement and natural sand as fine aggregate. The natural coarse aggregate was either crushed limestone or river bed gravel, while the coarse RCA was either RCA-M or RCA-V. The basic physical properties of these ingredients are given in Table 1 where the last column of the table shows the average residual mortar content of the two types of RCA used in this study. Notice that RCA-M and RCA-V contained 41% and 21% residual mortar, respectively. It is obvious that simple replacement of natural aggregate by RCA-M in a concrete mix would dramatically increase the total mortar content of the resulting concrete.

The specific gravity and absorption capacity of the aggregates were determined using standard testing procedures of ASTM [27]. The residual mortar content of RCA was determined based on a new method which involved subjecting the RCA to several freeze-and-thaw cycles in a sodium sulfate solution [23]. Both the natural and the recycled concrete aggregates had nominal maximum size of 19 mm and were presoaked before making the concrete mix while the fine aggregate was kept damp for 24 h before mixing.

2.2. Mixture proportions

Two groups of mixes each comprising three mix types were prepared. In Group I mixes the coarse aggregate was crushed limestone while in Group II mixes it was river gravel. The mixes ID and proportions are shown in Table 2. The three mix types in each group consisted of (1) mixes CL or CG containing 100% natural coarse aggregate and proportioned by the conventional method of ACI [18], (2) mixes CM and CG containing coarse RCA and were proportioned by the conventional method of ACI, and (3) mix EM and EG containing coarse RCA and proportioned by the EMV method [22]. The letters E and C in these designations refer to the

Table 1
Average physical properties of coarse and fine aggregates.

Aggregate	Moisture content (%)	Absorption content (%)	Specific gravity			RMC[a] (%)
			Bulk	SSD	Apparent	
RCA-M	1.1	5.4	2.31	2.42	2.64	41
RCA-V	1.3	3.3	2.42	2.50	2.64	23
Limestone	0.2	0.34	2.70	2.71	2.73	–
River gravel	0.2	0.89	2.72	2.74	2.79	–
River sand[b]	4	0.54	2.70	2.72	2.76	–

[a] Residual mortar content = oven-dry weight of residual mortar/oven-dry weight of RCA.
[b] Fineness modulus of 2.60.

Table 2
Mix proportions of concrete mixes.

Beam ID	RCA content (%)	Mix proportions (kg/m^3)						
		Water	Cement	Sand	Coarse aggregate		WRA[a] (ml)	AE[b](ml)
					RCA	Natural aggregate		
CM	100	156	349	888	792	0	1396	35
EM	63.5	151	335	630	720	414	1055	35
CL	0	193	430	808	0	835	None	92
CV	100	156	349	857	867	0	1047	35
EV	74.3	161	358	645	813	281	1132	38
CG	0	191	424	763	0	900	None	91
Mix designation nomenclature	E or C: mix proportioned based on EMV (E) or conventional method (C); and 2) M, V, L or G: mix made with RCA-M (M), RCA-V (V), natural limestone (L) or natural gravel (G)							

[a] Water reducing agent.
[b] Air entraining.

mixture proportioning method with E referring to the EMV method and C to the conventional method. The letters L, G, M and V refer to the type of coarse aggregate used in the particular mix, and they denote natural limestone, river gravel, RCA-M and RCA-V, respectively. Note that mixes CL and CG are conventional concrete mixes and serve as reference for the RCA concrete mixes (see Table 3).

Based on the writers experience, reasonable differences between the strength and density of the residual mortar and the fresh mortar as well as differences between the shape and density of the original virgin aggregate in RCA and the fresh natural aggregate shape has some, albeit generally small, effect on the overall properties of RCA-concrete compared to the companion natural aggregate concrete. It is presumed that severely deteriorated or damaged mortar in recycled concrete will generally not survive the crushing forces that are applied to convert concrete to RCA, thus the crushing process indirectly assures the quality of the residual mortar. Large differences among these properties will be reflected by the strength, density and elastic modulus of the RCA-concrete, which can be used in the assessment of the creep properties of the same concrete. However, the current research does not cover such large differences.

Table 3
Fresh and hardened properties of investigated concrete mixes.

Mix ID	Fresh properties			Hardened properties	
	Slump (mm)	Air content (%)	Fresh γ_c (kg/m^3)	f'_c (MPa) 28 days	Hardened γ_c (kg/m^3)
CM	75	5.9	2298	43.9	2290
EM	110	4.9	2338	41.4	2303
CL	160	6.4	2330	35.2	2324
CV	25	5	2378	45.9	2348
EV	70	5.6	2398	44.8	2364
CG	200	6.2	2358	34.1	2322

2.3. Test method

The creep tests were carried out following the procedures in ASTM C 512-02 [28]. The test specimens were standard 150×300 mm cylinders, which were demolded 24 h after casting, and moist cured in a 100% relative humidity chamber until the age of 7 days. After the moist curing period, the specimens were stored at a temperature of approximately 23.0 ± 1.0 °C and at a relative humidity of 50 ± 4% until the completion of the test.

The shrinkage tests were carried out following the procedure described in ASTM C 157/C 157M-99 [29]. The test specimens were $100 \times 100 \times 285$ mm prisms. They were moist cured inside the molds for 24 h and covered with plastic sheets to protect them from dripping water and demolded thereafter. After the initial comparator reading, the prisms were stored in lime-saturated water at 23 ± 2 °C until the age of 28 days. At the end of the curing period, a second comparator reading was taken and the specimens were stored in a drying room. Readings were taken after 4, 7, 14, and 28 days, and 8, 16, 32, and 64 weeks after the end of moist curing. During each measurement, first the reference bar was placed in the comparator, and the comparator dial was set to zero. Next, the specimen was placed in the comparator and reading was taken. Using the comparator readings, the shrinkage strain was calculated as

$$\varepsilon_{sh}(t) = \left(\frac{l_2 - l_1}{l_g}\right) \quad (1)$$

where $\varepsilon_{sh}(t)$ is the drying shrinkage strain of the specimen at time t, l_1 is the initial comparator reading, l_2 is the comparator reading at time t, and l_g is the effective gage length between the inner most ends of the Demec disks embedded in the specimens.

2.4. Creep instrumentation and test setup

Fig. 1 shows the creep jig used to perform the tests. It consisted of the header plates bearing on the ends of the loaded specimens, a hydraulic ram for applying the load, and threaded rods to equilibrate the compression applied to the creep specimens. In each jig three replicate specimens made of one of the concrete mixes were stacked on top of each other and loaded simultaneously. Between the test specimen and the steel bearing plate at each end of the stack, a supplementary non-instrumented concrete disk with 150 mm diameter and 75 mm thickness was placed. To maintain the load to approximately 2% of its initial value, the jigs were outfitted with a pressure gauge. Whenever the load had to be adjusted, the hydraulic jack was connected to a nozzle on the jig and the pressure was adjusted. The longitudinal strain in each specimen was measured using a Demec strain gauge with 200 mm gauge length. Strains were measured on three gauge lines spaced uniformly around the periphery of each specimen.

Nine cylinders were cast for each concrete mix; three were tested for compressive strength, three were used for creep test, and the remaining three were used as control specimens to measure shrinkage and other deformations due to causes other than applied load. All nine cylinders were kept under the same temperature and humidity environment throughout the relevant test period.

For all the creep specimens the initial loading age was 28 days. Just before applying the initial load, the compressive strength of each concrete mix was determined by testing three cylinders. Based on the average strength of these cylinders, the companion creep specimens were initially loaded to 40% of their strength. Strain readings were taken according to the following intervals: immediately after loading, 2 h and 6 h after the application of the load on the first day, daily thereafter for 1 week, weekly until the

Fig. 1. Creep test setup.

end of 1 month, and monthly until the end of at least 1 year. The load was frequently monitored and it was made sure that it did not fall more than 2% below its initial value. The strain readings on the control specimens were taken according to the same schedule as the loaded specimens.

2.5. Creep strain calculation

The total strain $\varepsilon_c^{Total}(t)$ at any time was calculated as the difference between the average strain readings of the loaded and control specimens. To determine the creep strain at any age, $\varepsilon_c(t)$, the instantaneous or initial strain immediately after loading, ε_0 was subtracted from the total strain at that age as follows:

$$\varepsilon_c(t) = \varepsilon_c^{Total}(t) - \varepsilon_0 \tag{2}$$

The unit creep or specific creep, $\varepsilon_{sp}(t)$, at any time t was calculated using:

$$\varepsilon_{sp}(t) = \frac{\varepsilon_c(t)}{\sigma_c} \tag{3}$$

where σ_c is the sustained stress on the specimen, which was 40% of the compressive strength of each specimen.

Since the initial strain is basically a function of the elastic modulus of concrete, for the sake of comparison, it is reasonable to remove the effect of this parameter by normalizing the creep strains with respect to this parameter. Alternatively, one can use the concept of creep coefficient, C_t, to account for this effect as follows

$$C_t = \frac{\varepsilon_c(t)}{\varepsilon_0} \tag{4}$$

Another alternative is to simply divide the total strain by initial strain and calculated the total creep coefficient as

$$C_t^{Total} = \frac{\varepsilon_c^{Total}(t)}{\varepsilon_0} \tag{5}$$

At initial loading ($t = 0$), C_t is zero while C_t^{Total} is equal to one.

In this investigation, for convenience the creep coefficient will be used, rather than creep strain, to compare the creep behavior of the different mixes because the former does not involve the initial strain.

3. Experimental results

3.1. Effect of mix proportioning method on creep and shrinkage

3.1.1. Effect on creep coefficient

Fig. 2 shows variation of the creep coefficient with time for all the mixes tested. With reference to Fig. 2a, it can be observed that among Group I mixes, mix EM, which is made with RCA-M and proportioned by the EMV method, has the lowest creep coefficient value compared to the companion mix CM, proportioned by the conventional method, and even lower than the reference mix CL made with 100% fresh natural aggregate. At the age of 245 days, the creep coefficient of EM was 34% lower than that of CL, while that of CM was 29% higher than that of CL.

Similarly, comparing the mixes in Group II in Fig. 2b, at 245 days after first loading, the creep coefficient of mix EV, which was proportioned by the EMV method, was 4% lower than that of the companion mix CG, made with virgin natural aggregates only, while that of mix CV, made with RCA and proportioned by the conventional method, was 14% higher than that of CG.

Since all other factors, except the mix composition, which are known to affect concrete creep such as w/c ratio, curing condition, temperature, and moisture, were the same for the three mixes in each group, the lower creep coefficient of mixes made with RCA and proportioned by the EMV method compared to the companion mixes made with RCA and proportioned by the conventional method may be ascribed to the lower total mortar content of the former mixes. On the other hand, the mixes made with RCA and proportioned by the EMV method had the same total mortar content as the companion mixes made entirely with virgin natural aggregates,

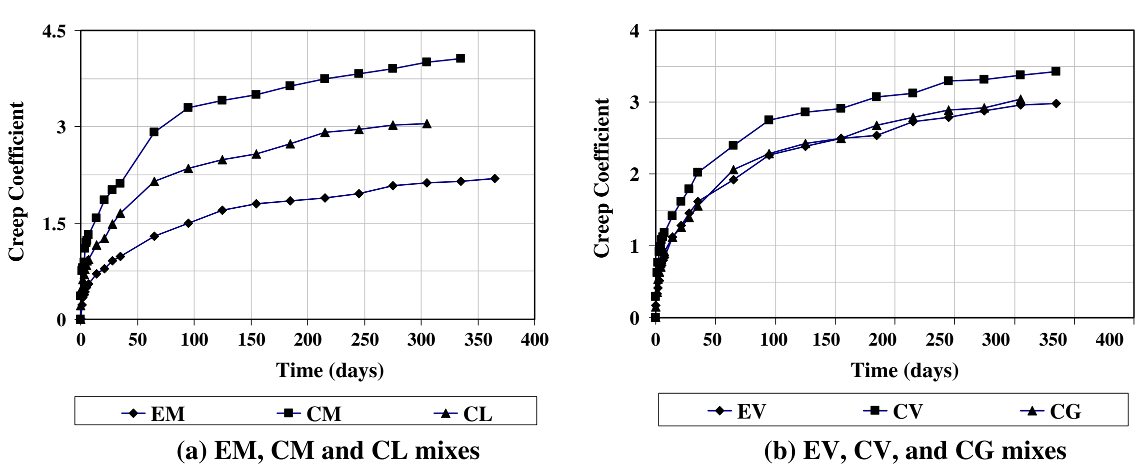

Fig. 2. The effect of mix proportioning method on the creep coefficient.

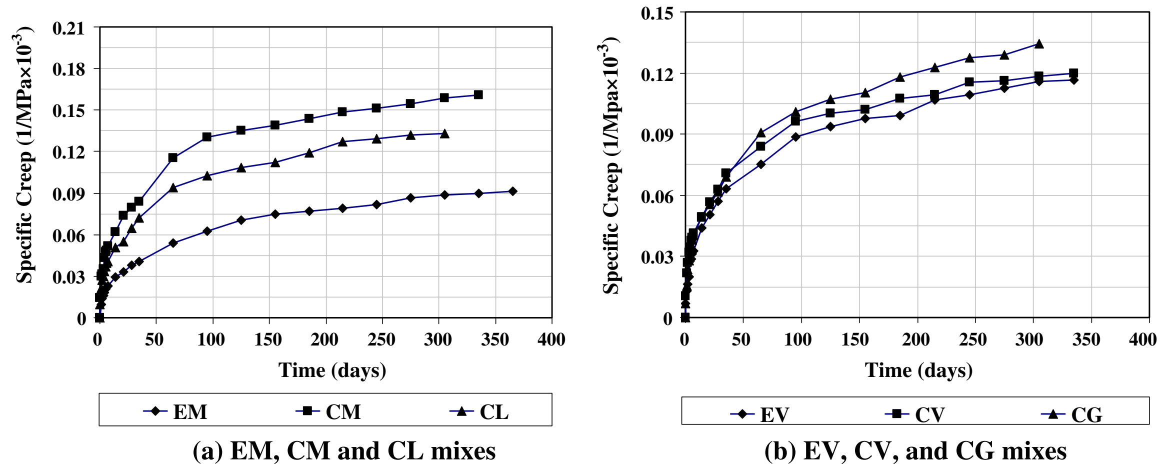

Fig. 3. The effect of mix proportioning method on the specific creep.

yet the RCA concrete mixes experienced lower creep. The lower creep in the latter case may be attributed to the fact that the total mortar in the mixes made with RCA partially consisted of residual mortar, which may be less susceptible to creep than the fresh mortar because of its age and the irreversible creep phenomenon.

3.1.2. Effect on specific creep

Since all the concrete mixes in this study did not have the same compressive strength and since the sustained stress was 40% of the compressive strength of each mix, the creep specimens were not subjected to the same stress in every case. In order to eliminate the effect of level of stress on the creep coefficient, the concept of specific creep will be used.

Fig. 3a and b shows the specific creep variation with time for the two groups of mixes. Once again, we observe that in both groups, the mixes made with RCA and proportioned by the EMV method have the lowest specific creep albeit the difference between the EV and CV mixes is not significant. At the age of 245 days after loading, the specific creep of mix EM was 36% lower while that of mix CM was 17% higher than that of reference mix CL. Mixes EV and CV, respectively, had 14% and 11% lower specific creep coefficient than reference mix CG. The reason for the higher specific creep of mix CG was its lower compressive strength than its companion mixes.

It is clear from the above results that RCA concrete is not inherently susceptible to higher creep; on the contrary, if the mixes were proportioned by the EMV method, they would be less prone to creep than even conventional concrete with similar composition.

3.1.3. Effect on shrinkage

Fig. 4 shows the shrinkage strain variation with time for the two groups of concrete mixes. In Fig. 4a we observe that at early age mix EM experienced the highest shrinkage compared to the companion mixes CM and CL. However, after the age of 75 days, the total shrinkage strain in mix CM started to exceed that in mix EM, but it was still higher than that of mix CL. At the age of 224 days, the shrinkage strain in mix EM was 7% and in mix CM 26% higher than in mix CL. Although both RCA concrete mixes in this group experienced higher shrinkage than the conventional concrete, the RCA mix proportioned by the EMV method experienced significantly less shrinkage than the companion mix proportioned by the conventional method. Once again this lower shrinkage may be ascribed to the smaller total mortar content of the mix proportioned by the EMV method. One reason for the higher early shrinkage of the RCA mixes may be the relatively easier loss of moisture from the RCA particles because it is likely that this is free water and is not required to hydrate the cement in the residual mortar which is already hydrated. It may be recalled that the RCA particles were soaked in water prior to making the concrete mixes and it is believed that most of this water would be lost relatively quickly.

Similarly, with reference to Fig. 4b, at early ages mix EV experienced the highest shrinkage strain compared to its companion mixes CV and CG. However, after the age of 45 days, the shrinkage strain in EV started to slow down until at the age of 224 days it became 15% less than that of mix CG. On the contrary, at the age of 224 days, the mix CV had 14% higher shrinkage strain than the

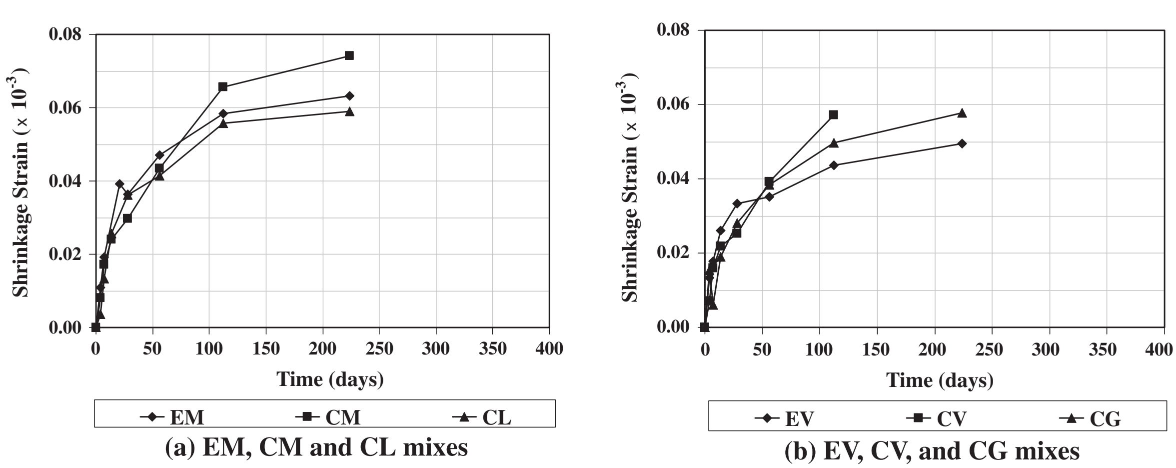

Fig. 4. The effect of mix proportioning method on the drying shrinkage strain.

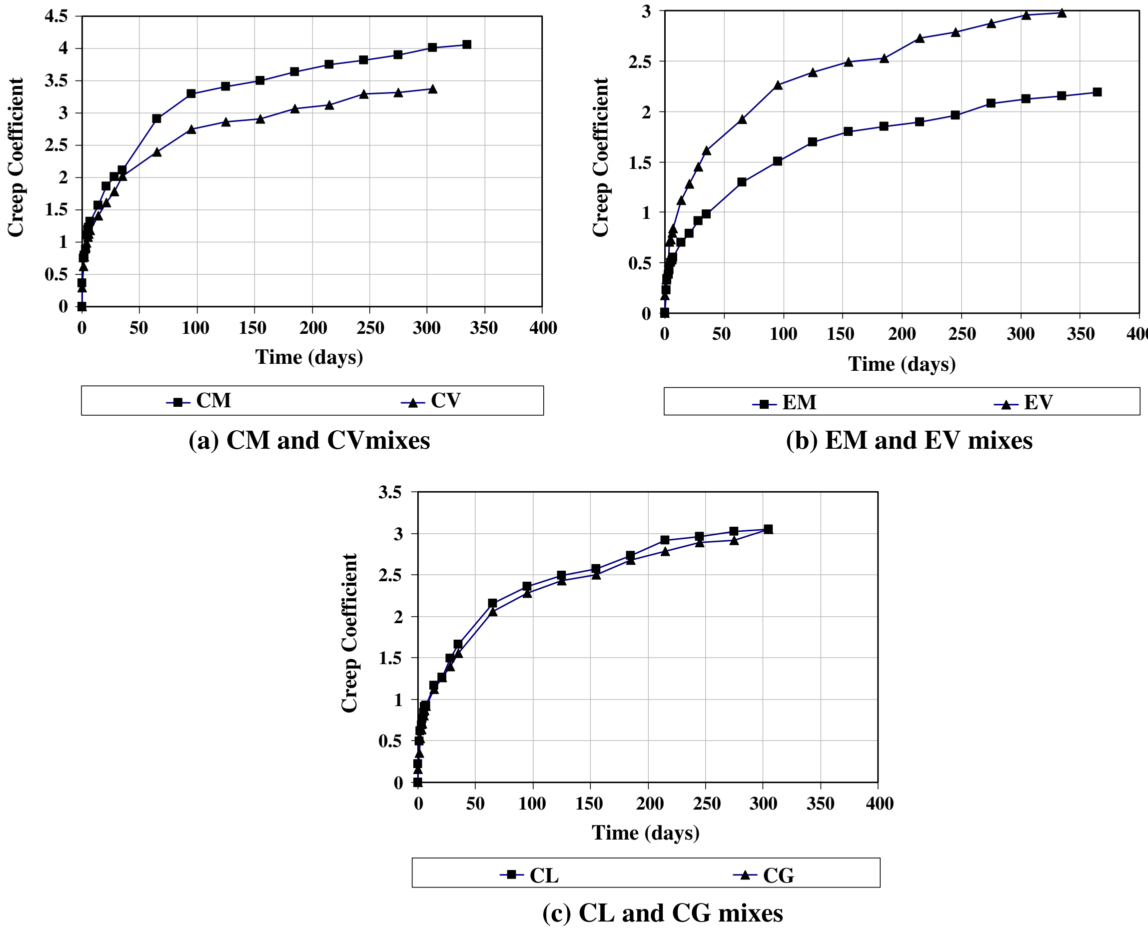

Fig. 5. Effect of aggregate type on creep coefficient.

mix CG. Based on these observations, it is obvious that the proposed EMV method yields RCA concrete mixes that experience less long-term creep and shrinkage than similar mixes proportioned by conventional methods.

3.2. Effect of aggregate type on creep and shrinkage

In this study two types of natural aggregates were investigated; namely, crushed stone and river gravel. Fig. 5a–c compares the creep coefficient variation with time for the pair of mixes proportioned by the same method, with the main differences between the two mixes being the type of coarse natural aggregate. In each case, one mix is made with virgin gravel or with RCA-V and the other with virgin crushed limestone or with RCA-M. If we compare the behaviors of mixes CM and CV in Fig. 5a, we notice that CM exhibits higher creep than CV. This behavior is expected because if one were to replace a certain fraction of the coarse natural aggregate in the reference mix by RCA-M versus RCA-V, the mix containing RCA-M would contain more total mortar and less natural aggregate than the mix containing RCA-V because RCA-M was made of 41% residual mortar versus RCA-V which was made of 23% residual mortar. Therefore, the greater mortar content of RCA-M is responsible for the higher creep in mix CM. By contrast, Fig. 5b shows mix EM to have experienced less creep than mix EV. If we look at the composition of these mixes in Table 2, we observe that mix EV has higher fresh mortar content (1164 kg/m^3) than mix EM (1116 kg/m^3). Clearly, this difference is not large enough to justify the magnitude of the observed difference between the creep coefficients of the two mixes. Therefore, another possible reason may be the tendency of the residual mortar in RCA-V to creep more than the residual mortar in RCA-M. It was determined that the two residual mortars did not have the same composition because RCA-V contained fly ash while RCA-M did not [22]. The creep characteristics of limestone versus river gravel do not seem to be responsible for the above difference. The latter is confirmed by the results shown in Fig. 5c, which shows the creep coefficients of mixes CL and CG. Since these are conventional mixes with similar composition, as the latter figure indicates they have practically the same creep coefficient throughout the test period. Thus the type of natural aggregate in the present mixes had little influence on their creep coefficients.

Fig. 6 illustrates the effect of aggregate type on the drying shrinkage of the pair of mixes proportioned by the same method. As Fig. 6a and c indicate the aggregate type had little effect on the drying shrinkage of mixes proportioned by the conventional method, with or without RCA. On the other hand, Fig. 6b shows that in the mixes proportioned by the EMV method, mix EM exhibited higher shrinkage than mix EV. Since the fresh mortar contents of these mixes were similar and since the coarse natural aggregate type seems to have had little effect on shrinkage, as indicated by the results in Fig. 6c, the observed difference can be ascribed to the difference between the shrinkage properties of the residual mortars in these aggregates.

4. Modifications of existing creep and shrinkage models for application to RCA-concrete

Some phenomenological models are available for predicting creep and shrinkage of conventional concrete as a two-phase material (aggregate and mortar). These models relate concrete creep

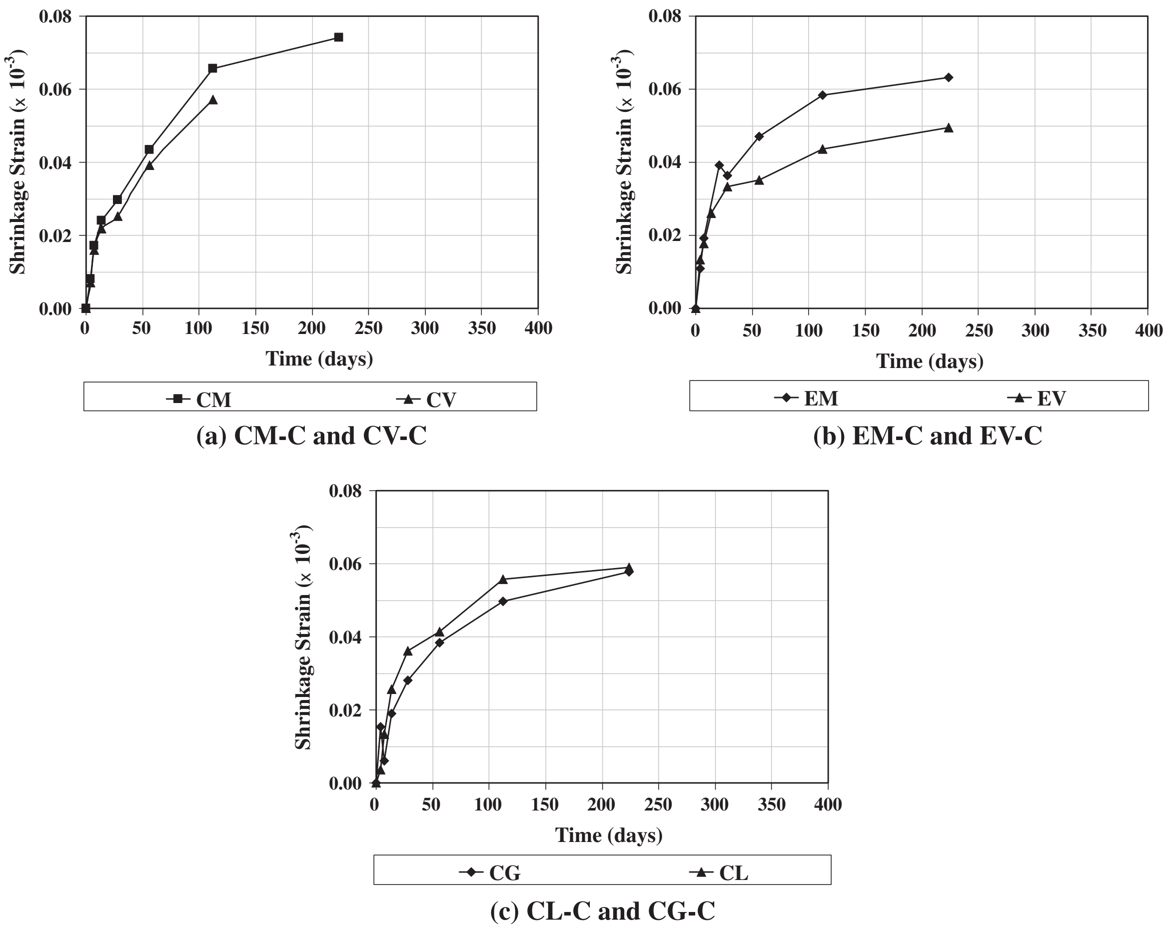

Fig. 6. Effect of aggregate type on drying shrinkage.

and shrinkage to the volume fractions of its principal constituents (i.e., aggregate and mortar) and to the pertinent properties of its cement paste. However, these models cannot be directly applied to RCA-concrete because it contains two additional phases; viz. the natural aggregate and residual mortar in RCA. Therefore, to apply existing models to RCA, they need to be suitably modified. In the following an attempt is made to propose modifications, but due to the limited scope of the present test data, ascertaining the generality of the modified expressions requires further investigation and more data.

4.1. Modified creep model

One of the models for creep of conventional concrete is proposed by Neville [30], in which the creep coefficient of concrete (c_{NAC}) is related to the creep coefficient of its cement paste and to the volume fraction of its natural aggregate (V_{NA}^{NAC}) as follows

$$\log\frac{c_p}{c_{NAC}} = \alpha_{NAC}\log\frac{1}{1-V_{NA}^{NAC}} \tag{6}$$

where c_p is the creep coefficient of neat cement paste of the same quality as used in the concrete under study, and α_{NAC} is a parameter defined as:

$$\alpha_{NAC} = \frac{3(1-\mu_{NAC})}{1+\mu_{NAC}+2(1-2\mu_{NA})\frac{E_{NAC}}{E_{NA}}} \tag{7}$$

where μ_{NA} is the Poisson's ratio of natural aggregate, μ_{NAC} is the Poisson's ratio of concrete, E_{NA} is the elastic modulus of natural aggregate, and E_{NAC} is the elastic modulus of concrete. Natural aggregate in the context of Eq. (6) refers to the coarse and fine aggregate ensemble. In Eq. (6) full cement hydration is assumed, which may be considered reasonable for concrete after the age of 1 year. Furthermore, in practice it is neither easy nor feasible to determine or control the extent of cement hydration.

To apply the above equation to RCA-concrete, we begin with the fundamental assumption that RCA-concrete is a two-phase material with its phases comprising the total mortar (TM) and total natural coarse aggregate (TNA). As stated earlier, relatively reasonable differences among the properties of the fresh and residual mortar on the one hand, and among the properties of the virgin and fresh aggregate on the other, would have relatively small effect on the mechanical properties of RCA-concrete. The total mortar includes total cement paste (new cement paste plus residual cement paste contained in RCA) plus total natural fine aggregate (new natural fine aggregate plus residual natural fine aggregate contained in RCA). The total natural coarse aggregate is the sum of the volumes of new coarse natural aggregate and the coarse natural aggregate contained in RCA, termed original virgin aggregate (OVA). In this discussion, the word natural aggregate refers to the total natural aggregate, i.e. coarse plus fine. For the types of coarse natural aggregates used in this study, it is reasonable to assume [31] $\mu_{NA} \approx \mu_{RCA}$ and $\mu_{NAC} \approx \mu_{RAC}$. Accordingly, Eqs. (6) and (7) can be modified for RCA-concrete as follows:

$$\log\frac{c_p}{c_{\text{RCA-concrete}}} = \alpha_{\text{RCA-concrete}}\ \log\frac{1}{1-V_{NA}^{\text{RCA-concrete}}} \tag{8}$$

where $C_{\text{RCA-concrete}}$ is the creep coefficient of RCA-concrete, $V_{NA}^{\text{RCA-concrete}}$ is the total natural aggregate volume fraction in RCA-concrete, and $\alpha_{\text{RCA-concrete}}$ is a parameter defined as:

$$\alpha_{\text{RCA-concrete}} = \frac{3(1-\mu_{NAC})}{1+\mu_{NAC}+2(1-2\mu_{NA})\frac{E_{\text{RCA-concrete}}}{E_{NAC}}\times\frac{E_{NAC}}{E_{NA}}} \quad (9)$$

where $E_{\text{RCA-concrete}}$ is the elastic modulus of RCA-concrete.

Since the creep behavior of RCA-concrete will be dominated by its fresh mortar content and creep properties, it is reasonable to assume that the cement paste in RCA-concrete will have properties similar to those of the cement past in the NA-concrete. Bearing this assumption in mind and dividing Eq. (6) by Eq. (8), the creep coefficient of RCA-concrete can be correlated to the corresponding creep coefficient of NA-concrete as follows:

$$\frac{C_{\text{RCA-concrete}}}{C_{NAC}} = \frac{\left(1-V_{NA}^{\text{RCA-concrete}}\right)^{\alpha_{\text{RCA-concrete}}}}{\left(1-V_{NA}^{NAC}\right)^{\alpha_{NAC}}} \quad (10)$$

For the materials used in this study, it is reasonable to let $\mu_{NA} \approx \mu_{RCA} \approx 0.20$ and $\frac{E_{NAC}}{E_{NA}} \approx 0.5$ [31]. Therefore, Eq. (10) can be written as:

$$\frac{C_{\text{RCA-concrete}}}{C_{NAC}} = \frac{\left(1-V_{NA}^{\text{RCA-concrete}}\right)^{\frac{2.4}{1.20+0.6E_{\text{RCA-concrete}}/E_{NAC}}}}{\left(1-V_{NA}^{NAC}\right)^{1.8}} \quad (11)$$

By using the appropriate elastic modulus values and aggregate contents of the constituents of the EM and EV mixes, which were proportioned by the EMV method, Eq. (11) will yield approximately the same creep coefficient for EM and EV as the their companion NA-concrete mixes CL and CG, respectively, because each of the above RCA-concrete mixes has nearly equal elastic modulus and natural aggregate content as its companion NA-concrete mix.

On the other hand, Eq. (11) did not predict the creep of CM and CV mixes, which were proportioned by the conventional mix proportioning method. Equation (11) predicted the creep of CM to be 11% higher than that of CL and the creep of CV to be 7% lower than that of CG, while in the experiment they were measured to be 29% and 14% higher, respectively. However, by ignoring the volume of fine natural aggregate when calculating the volumetric ratio of natural aggregate in Eq. (11, the equation predicts the creep of the CM and CV mixes more accurately. In the latter case, the creep of CM and CV mixes are predicted to be 28% and 17% higher than those of the companion CL and CG mixes, respectively. As shown earlier, based on test results, the creep coefficient of CM and CV mixes at the age of 245 days were found 29% and 14% higher than those of CL and CG mixes, respectively. It should be pointed out that Eq. ((11) is not sensitive to reasonable deviations from the assumption of $\frac{E_{NAC}}{E_{NA}} \approx 0.5$. A ±15% deviation from the 0.5 ratio changes the predicted creep coefficient value by less than ±1.5%.

The larger discrepancy between the predicted and observed creep coefficients of mix CV versus CM may be attributed to the presence of fly ash in the residual mortar of RCA-V, which alters the parameter c_p because the cement past is no longer made of neat cement alone. It should be stated that due to lack of adequate data, the proposed approach (Eq. (11)) is not recommended for application to mortars containing supplementary cementitious materials because even for conventional concrete, as stated by Neville [30], "quantitatively generalizations about creep of concrete containing fly ash or ground granulated blast furnace slag are not possible."

4.2. Modified shrinkage model

One of the suggested models in the literature for predicting the shrinkage of conventional concrete is [21]

$$S_{NAC} = S_p(1-V_{NA}^{NAC})^n \quad (12)$$

where S_{NAC} is the concrete shrinkage strain at a given time and under certain environmental conditions, S_p is the shrinkage strain of a neat cement paste of the same quality as used in the companion concrete at the same time and under the same conditions, V_{NA}^{NAC} is the volume fraction of aggregate n is an empirical exponent varying between 1.2 and 1.7 (average of 1.45).

As stated earlier, if RCA-concrete is treated as a two-phase material comprising total mortar (TM) and total natural aggregate (TNA), Eq. (12) can be modified for RCA-concrete as follows:

$$S_{\text{RCA-concrete}} = S_p\left(1-V_{NA}^{\text{RCA-concrete}}\right)^n \quad (13)$$

Note that in the Eq. (13), the term natural aggregate (NA) refers to the sum of total natural coarse aggregate plus total natural fine aggregate. Assuming the cement in RCA-concrete to have the same shrinkage characteristics as the cement in NAC and dividing Eq. (13) by Eq. (12), the shrinkage of RCA-concrete can be related to the corresponding shrinkage of NA-concrete as follows:

$$\frac{S_{\text{RCA-concrete}}}{S_{NAC}} = \left(\frac{1-V_{NA}^{\text{RCA-concrete}}}{1-V_{NA}^{NAC}}\right)^n \quad (14)$$

By using the pertinent aggregate contents of the EM and EV mixes in the current study, Eq. (14) will yield for these mixes shrinkage strain values comparable to the shrinkage strains of CL and CG mixes, and this finding agrees with the current experimental results.

On the other hand, Eq. (14) did not predict well the shrinkage of CM and CV mixes. At the age of 246 days, for the CM mix, its predicted value was 18% higher than that of its companion NA-concrete mix CL while for the CV mix it was 6% lower than that of its companion mix CG. Based on experimental data, at the same age, CM experienced 26% higher shrinkage than CL and CV experienced 14% higher shrinkage than CG. However, if in Eq. (14) the volume of natural is assumed to be only the volume of coarse natural aggregate, rather than coarse plus fine aggregate, the equation would predict the creep of CM and CV mixes more accurately. Based on the preceding assumption, Eq. (14) predicted the creep of CM to be 32% higher than that of CL and the creep of CV 20% higher than that of CG. The latter percentages compare favorably with the corresponding experimental values of 26% and 14%. The higher discrepancy between the observed and predicted shrinkage of CV mix, compared to the CM mix, may be partly attributed to the presence of fly ash in the residual mortar of RCA-V. The proposed modified expression is not recommended for application to mortars containing supplementary cementitious materials and would need verification by additional test data.

4.3. Application of ACI and CEB-FIP creep and shrinkage methods to RCA-concrete

In this section the applicability of common expressions used to predict the creep coefficient and drying shrinkage of normal concrete to RCA-concrete is investigated. The empirical formulas recommended by ACI Committee 209 [32] and CEB-FIP [33] will be investigated. These formulas are not given here because they are readily available in text books [34] and other Refs. [32,33].

4.4. Creep

Fig. 7 illustrates the experimental and predicted creep coefficient variation with time according to the empirical equations proposed by ACI Committee 209 and CEB-FIP for the mixes made with RCA-M and RCA-VA, respectively. For comparison purposes, all of the experimental creep coefficient-time curves have been normalized to the highest creep coefficient measured for each mix. Similarly, for each mix its computed creep coefficient, based on the empirical formulas, was normalized by its calculated creep coeffi-

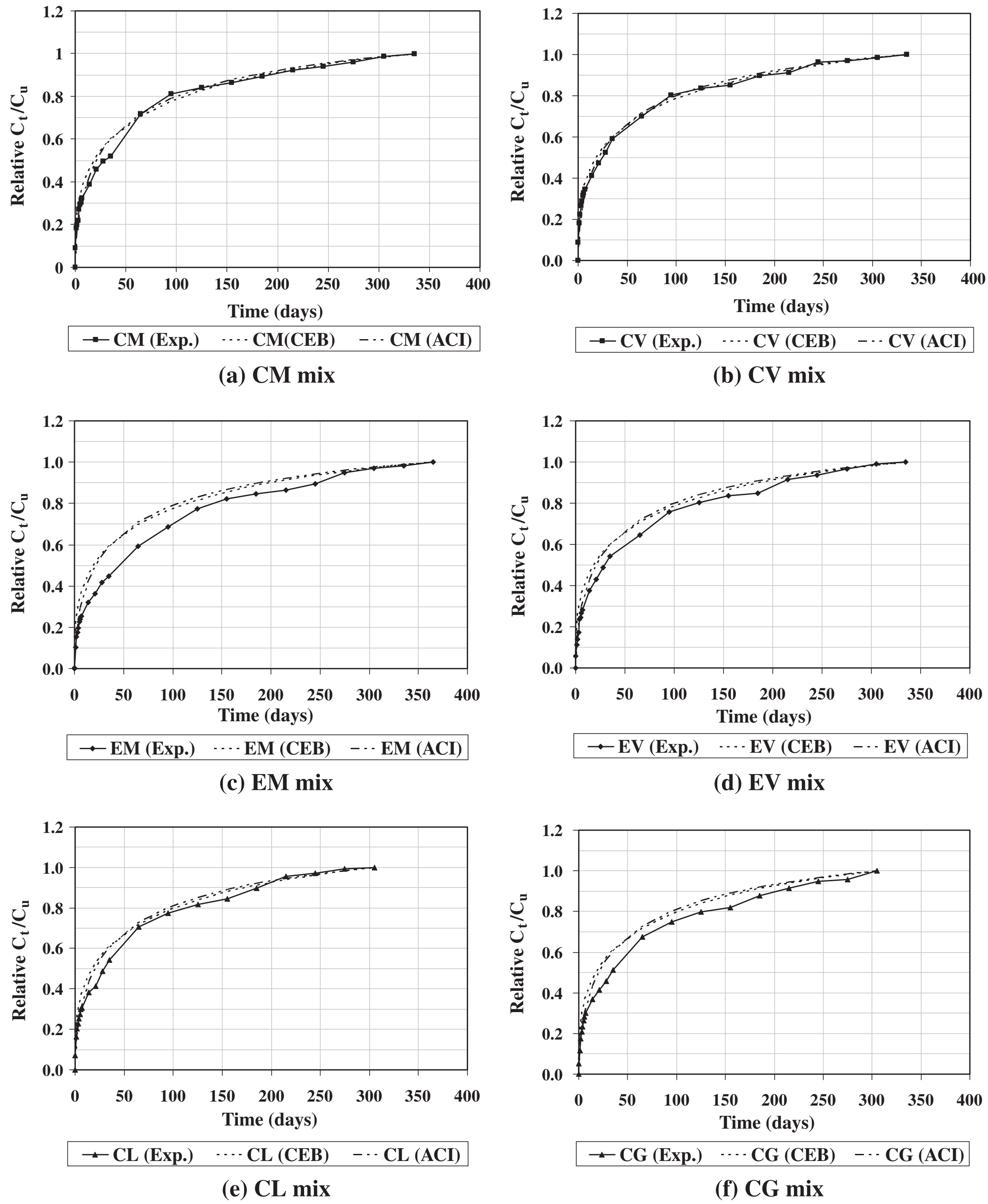

Fig. 7. Relative creep coefficient versus time relationship based on experimental data and CEB and ACI equations for different mixes.

cient corresponding to the time of maximum creep strain in the test.

Generally, the predicted normalized creep coefficient variation with time based on both the CEB and the ACI formulas were found to be in good agreement with the observed ones for all the mixes, irrespective of aggregate type and mix proportioning method. At early ages, the observed creep was found to be slightly lower than the predicted creep by both the CEB-FIP and the ACI methods. This was particularly evident for mix EM.

If one were to examine the ACI formula, one would discover that the fine aggregate and air contents are two of several factors that affect the creep properties of NA-concrete; increasing either one would lead to an increase in creep of concrete. By simply applying these methods to RCA-concrete, the fine aggregate and air contents of residual mortar would be ignored yet they affect the creep of RCA-concrete. Since there might not be enough information regarding the composition of the residual mortar in RCA, one way of indirectly taking these quantities into account would be to introduce a new factor or coefficient. This is referred to as *residual mortar coefficient* (K_{RM}), and it can be derived by using Eq. (9), which is the proposed empirical equation for creep of RCA-concrete. For RCA-concrete mixes proportioned by the EMV method, the creep of RCA-concrete is predicted similar to that of normal concrete due to their equivalent total mortar volume. Therefore, the residual mortar coefficient can be taken equal to 1 ($K_{RM} = 1$). However, the creep of a RCA-concrete mix proportioned by conventional methods is predicted to be higher than that of NA-concrete due to its higher total mortar volume than the companion

NA-concrete. Consequently, by assuming $\alpha_{NAC} \approx \alpha_{\text{RCA-concrete}} = 1.33$ (using Eq. (7) and assuming $\mu_{NA} \approx \mu_{RCA} \approx 0.20$ and $\frac{E_{NAC}}{E_{NA}} \approx 0.5$), Eq. (9) can be written as:

$$C_{\text{RCA-concrete}} = \left(\frac{1 - V_{NA}^{\text{RCA-concrete}}}{1 - V_{NA}^{NAC}}\right)^{1.33} \times C_{NAC} \tag{15}$$

Since C_{NAC} can be found by the ACI method, the $\left(\frac{1-V_{NA}^{\text{RCA-concrete}}}{1-V_{NA}^{NAC}}\right)^{1.33}$ term can be taken as a new coefficient which accounts for the effect of residual mortar. Therefore,

$$K_{RM} = \left(\frac{1 - V_{NA}^{\text{RCA-concrete}}}{1 - V_{NA}^{NAC}}\right)^{1.33} \tag{16}$$

Since in the conventional mix proportioning method, RCA replaces NA by weight or volume, the volume of coarse RCA in RCA-concrete can be taken equal to the volume of the coarse NA volume in NA-concrete. Furthermore, the nominator in Eq. (16) is equal to the total mortar volume in RCA-concrete, including residual and fresh mortar volumes. Therefore, Eq. (16) can be rewritten as:

$$K_{RM} = \left(\frac{V_{NM}^{\text{RCA-concrete}} + V_{RM}^{\text{RCA-concrete}}}{1 - V_{RCA}^{\text{RCA-concrete}}}\right)^{1.33} \tag{17}$$

Basically, the volume and weight of each RCA particle can be presented as the summation of the volume and weight of its two components:

$$V_{RCA} = V_{RM} + V_{OVA} \tag{18}$$

$$W_{OD}^{RCA} = W_{OD}^{RM} + W_{OD}^{OVA} \tag{19}$$

The volume of RCA, residual mortar and original virgin aggregate in RCA can be calculated by dividing their oven-dry weight by their corresponding bulk specific gravities as:

$$V_{RCA} = \frac{W_{OD}^{RCA}}{SG_b^{RCA}} \tag{20}$$

$$V_{RM} = \frac{W_{OD}^{RM}}{SG_b^{RM}} \tag{21}$$

$$V_{OVA} = \frac{W_{OD}^{OVA}}{SG_b^{OVA}} \tag{22}$$

where V_{RCA} is the volume of RCA, V_{RM} is the volume of residual mortar, V_{OVA} is the volume of original virgin aggregate, SG_b^{RCA} is the bulk specific gravity of RCA, SG_b^{RM} is the bulk specific gravity of residual mortar, SG_b^{OVA} is the bulk specific gravity of original virgin aggregate, W_{OD}^{RCA} is the oven-dry weight of RCA, W_{OD}^{RM} is the oven-dry weight of residual mortar, and W_{OD}^{OVA} is the oven-dry weight of original virgin aggregate. Based on the definition of residual mortar content (RMC) as

$$RMC = \frac{W_{OD}^{RM}}{W_{OD}^{RCA}} \tag{23}$$

the bulk specific gravity of residual mortar can be obtained by using Eqs. (18)–(23) as follows:

$$SG_b^{RM} = \frac{RMC}{\frac{1}{SG_b^{RCA}} - \frac{1-RMC}{SG_b^{OVA}}} \tag{24}$$

Knowing the bulk specific gravity of residual mortar (Eq. (24)), the bulk specific gravity of RCA, and the residual mortar content (RMC), the volume of residual mortar can be calculated using Eqs. (20), (21), (23), and (24) as follows:

$$V_{RM}^{\text{RCA-concrete}} = V_{RCA} \times RMC \times \frac{SG_b^{RCA}}{SG_b^{RM}} \tag{25}$$

By using Eqs. (24) and (25), Eq. (17) can be rearranged as:

$$K_{RM} = \left[\frac{1 - \left((1 - RMC) \times \frac{SG_b^{RCA}}{SG_b^{OVA}}\right) \times V_{RCA}^{\text{RCA-concrete}}}{1 - V_{RCA}^{\text{RCA-concrete}}}\right]^{1..33} \tag{26}$$

Eq. (26) can be used as a new coefficient in both the ACI and CEB recommended methods in order to take into account the effect of residual mortar in RCA on the creep of the pertinent RCA-concrete. Knowing the volume of coarse RCA in a unit volume of RCA-concrete ($V_{RCA}^{\text{RCA-concrete}}$), the residual mortar content (RMC), the bulk specific gravities of RCA (SG_b^{RCA}) and the original virgin aggregate (SG_b^{OVA}), the residual mortar coefficient values of 1.35 and 1.22 were calculated for CM and CV mixes, respectively (compared to the observed values of 1.29 and 1.14, respectively, at the age of 245 days). Since determining SG_b^{OVA} might not be practical, Eq. (26) can be simplified by assuming $\frac{SG_b^{RCA}}{SG_b^{OVA}} \approx 1$, which leads to

$$K_{RM} = \left(\frac{1 - (1 - RMC) \times V_{RCA}}{1 - V_{RCA}}\right)^{1.33} \tag{27}$$

Using Eq. (27), residual mortar coefficient values of 1.28 and 1.15 were found for CM and CV mixes, respectively, which are only 4% lower than the calculated values by Eq. (25).

4.5. Shrinkage

Fig. 8 illustrates the experimental and predicted drying shrinkage strain variations with time for all the mixes tested in this study. The predicted values are based on the empirical methods of ACI Committee 209 and CEB-FIP. For comparison purposes, for each mix its experimental shrinkage strain–time curves are normalized by the largest measured shrinkage strain, which always occurred at the end of the test period. Similarly, for each mix, its predicted shrinkage strain values were normalized by the its shrinkage strain corresponding to the time in the experiment at which maximum shrinkage strain was measured.

Generally, the predicted normalized drying shrinkage strain variation with time according to both the CEB and ACI methods were found to agree well with the observed ones for all RCA- and NA-concrete mixes, irrespective of aggregate type or mix proportioning method.

However, by examining the ACI method, it can be observed that the fine aggregate, cement and air contents of conventional NA-concrete are three of the factors which affect its shrinkage properties. Increasing any of these quantities leads to an increase in the shrinkage of concrete. By simply applying the conventional methods to RCA-concrete, and by treating coarse RCA as simply another type of aggregate, the effects of the cement, fine aggregate and air contents of RCA on shrinkage of RCA-concrete are disregarded, which would lead to inaccurate prediction. On the other hand, determining these quantities for RCA may be onerous. Therefore, to resolve this dilemma and for simplicity, we will introduce a new coefficient which would indirectly take these factors into account. This coefficient is called the *residual mortar coefficient* (S_{RM}) and can be derived by using the proposed Eq. (14) for drying shrinkage of RCA-concrete.

For RCA-concrete mixes proportioned by the proposed EMV method, the shrinkage of RCA-concrete is predicted to be similar to that of NA-concrete due to their equivalent total mortar volumes. Therefore, the residual mortar coefficient can be taken equal to 1 ($S_{RM} = 1$). However, the shrinkage of RCA-concrete mixes proportioned by conventional method is predicted to be higher than that of NA-concrete due to its higher total mortar volume

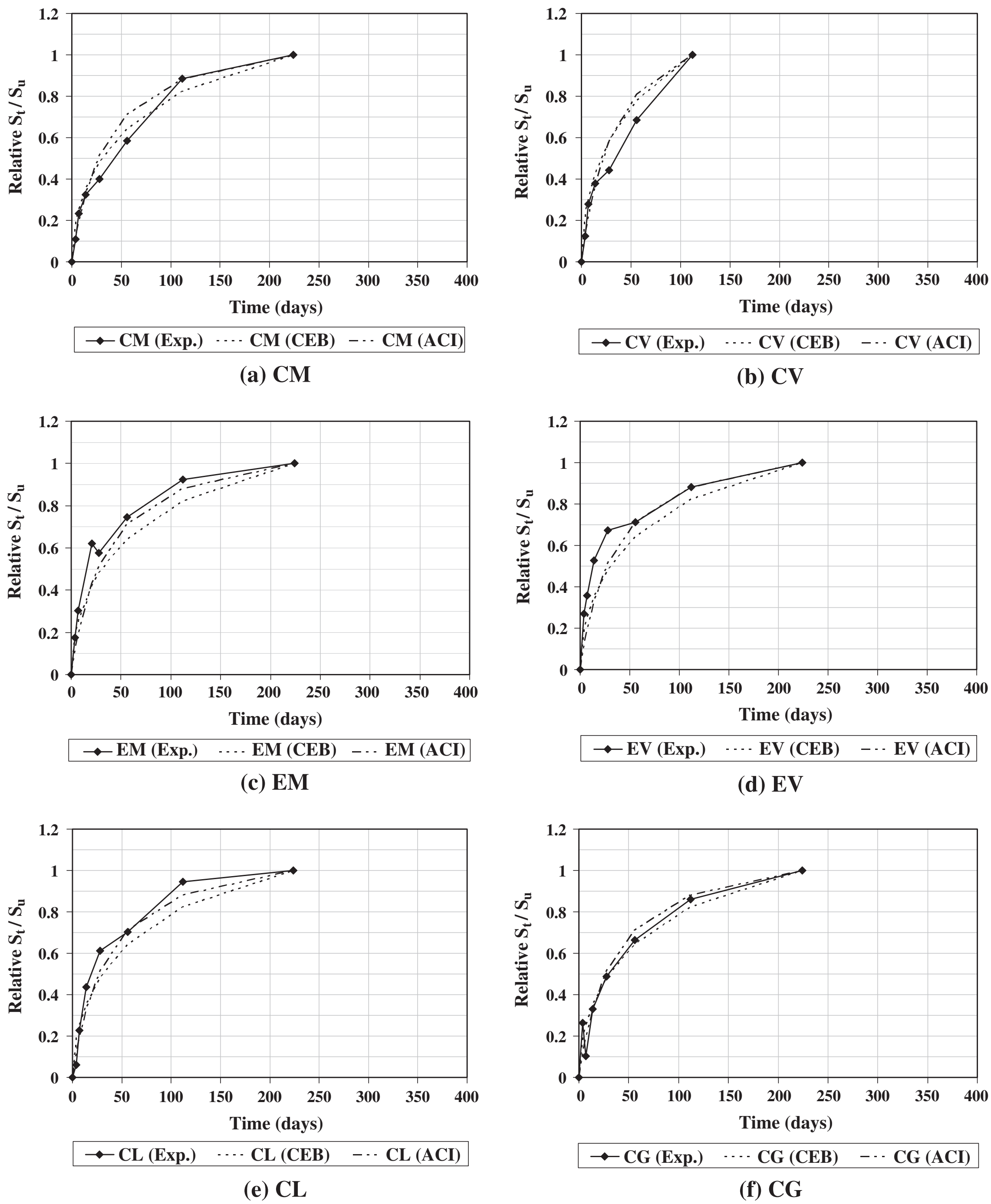

Fig. 8. Relative shrinkage strain versus time relationship based on experimental data and CEB and ACI equations for different mixes.

compared to that its companion NA-concrete. By assuming an average value of 1.45 for n, Eq. (14) can be rewritten as:

$$S_{RAC} = \left(\frac{1 - V_{NA}^{\text{RCA-concrete}}}{1 - V_{NA}^{NAC}}\right)^{1.45} \times S_{NAC} \tag{28}$$

Using Eqs. (24) and (25), Eq. (28) can be rearranged as:

$$S_{RM} = \left[\frac{1 - \left((1 - RMC) \times \frac{SG_b^{RCA}}{SG_b^{OVA}}\right) \times V_{RCA}^{\text{RCA-concrete}}}{1 - V_{RCA}^{RAC}}\right]^{1.45} \tag{29}$$

Eq. (29) can be used as an additional coefficient in both the ACI and CEB shrinkage prediction methods in order to make them applicable to RCA-concrete. For mixes CM and CV, Eq. (29) gives residual mortar coefficient values of 1.36 and 1.24, respectively, versus their observed values of 1.26 and 1.14 at the age of 224 days, which compare reasonably well. On the other hand, in practice determining SG_b^{OVA} might not be feasible; therefore, Eq. (29) can be further simplified by assuming $\frac{SG_b^{RCA}}{SG_b^{OVA}} \approx 1$, which would lead to

$$S_{RM} = \left(\frac{1 - (1 - RMC) \times V_{RCA}}{1 - V_{RCA}}\right)^{1.45} \tag{30}$$

Eq. (30) gives residual mortar coefficient values of 1.31 and 1.17 for the CM and CV mixes, respectively which are only 6% lower than the values given by Eq. (29), but are in fact closer to the corresponding experimental values than those obtained from Eq. (29). In practical applications, the above differences are within the acceptable range.

5. Conclusions

In this investigation a new concrete mixture proportioning method, called EMV, is used to investigate the creep characteristics of RCA-concrete. Based on the results of the investigation, the following conclusions are reached:

- The effect of mix proportioning method on the creep and shrinkage of concrete produced with RCA was quite noticeable. Generally, the RCA-concrete mixes proportioned by the EMV method experienced lower or comparable creep and shrinkage as the companion NA-concrete mixes, while the RCA-concrete mixes proportioned by the conventional method always experienced higher creep than the companion NA-concrete mixes.
- For the types of natural aggregates involved in the current investigation, the effect of aggregate type on creep was more noticeable in RCA-concrete mixes proportioned with conventional mix proportioning methods than in the NA-concrete mixes. This is attributed to the residual mortar in RCA rather than its natural aggregate type.
- The predicted creep and shrinkage strains of RCA-concrete mixes based on the proposed models in this study, which relate the creep and shrinkage of a RCA-concrete to those of a companion NA-concrete via the total natural aggregate volume fraction of each concrete mix, were found to be in reasonable agreement with the corresponding experimental strains for all the RCA-concrete mixes proportioned by the conventional or the EMV method.
- The normalized creep coefficient and drying shrinkage strain variation with time for all the tested concrete mixes, irrespective of aggregate type or mix proportioning method, were found to agree well with their predicted variations according to both the CEB and ACI empirical methods.
- The current ACI and CEB empirical methods for predicting creep and drying shrinkage in conventional concrete can be applied to RCA-concrete provided a so-called residual mortar factor is introduced. This factor accounts for the effect of residual mortar volume fraction in RCA-concrete on its creep and shrinkage. By applying the residual mortar coefficients proposed in this study, in conjunction with the ACI and CEB creep and shrinkage prediction methods, good agreement was observed between the predicted and experimentally measured creep and shrinkage strains for all the test specimens, but more data is need to ascertain the generality of the proposed expressions.

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