Deferred strain and cracking under sustained loading can be more prominent in self-consolidating concrete (SCC) used in repair applications than conventional concrete given its higher paste content. Flexural creep and subsequent creep recovery were monitored over 19 months tests for SCC, fiber-reinforced conventional vibrated concrete (FR-CVC), fiber-reinforced self-consolidating mortar (FR-SCM). Synthetic and steel fibers were used. Expansive agent (EA) was employed in FR-SCC with synthetic fibers. Fiber volumes of 0.5% and 0.8% were used in FR-CVC/FR-SCC and FR-SCM, respectively. Restrained shrinkage was also determined. The overall creep performance was based on the control of deflected deflection, crack opening, and strain in steel and concrete. The use of fibers enhanced creep performance by 5 to 7 times compared to SCC. FR-SCC with steel fibers provided 45% higher creep performance than FR-SCC with synthetic fibers. The incorporation of EA in FR-SCC enabled 80% additional enhancement of creep performance. The FR-SCC and FR-SCM mixtures exhibited crack widths lower than 0.2 mm at service loads as high as 70% of nominal load. The creep recovery of the FR-SCC was on the order of 20% to 70%, regardless of mixture type. Flexural creep and restrained shrinkage tests indicated similar tendencies of concrete performance. The best performance was obtained for the FR-SCC made with EA, followed by FR-SCC, then SCC and FR-SCM.

1. Introduction

Concrete used in infrastructure rehabilitation can be exposed to severe winter conditions with freeze-thaw cycles and de-icing salt exposure. These factors, in addition to service loads, can increase the risk of cracking, especially in the case of repair materials subjected to restrained shrinkage. Cracking can significantly affect durability and serviceability of concrete structures and reduce service life.

Given the higher paste content of self-consolidating concrete (SCC), shrinkage and creep can be up to 30% greater than that of conventional vibrated concrete (CVC) (Heirmana et al. 2008; Khayat and Long 2010; Long and Khayat 2011; Loser and Leemann 2009; Mazzotti and Savoia 2009; Aslani and Nejadi 2013; fib 2010; TC-242-MDC 2015; Kassimi and Khayat 2020). Creep, shrinkage, and cracking sensitivity can be affected by environmental conditions (curing method and relative humidity), member structure (size, geometry, volume-to-surface ratio, construction sequence, and cracking level), and loading history (age at the beginning of loading and load level and duration of sustained loading). They can also be affected by material properties, such as type and content of cement, supplementary cementitious materials, and chemical admixtures. Other factors include paste volume, water-to-cement ratio, aggregate properties (stiffness, content, and texture of coarse aggregate), elastic modulus of the concrete, as well as the elastic modulus of the fiber, fiber volume \( V_f \), fiber type, fiber length and diameter, and fiber orientation (Heirmana et al. 2008; Loser and Leemann 2009; Aslani and Nejadi 2013; fib 2010; TC-242-MDC 2015; Kassimi and Khayat 2020). Creep, shrinkage, and cracking sensitivity can be affected by fiber length and diameter, and fiber orientation. Heirmana et al. (2008) concluded that the use of fibers can increase the creep parameters, unlike fiber length. Vasanelli et al. (2013) concluded that steel and polyester fibers have fairly the same influence on the long-term cracking behavior of beams. On the other hand, other studies concluded that the use of fibers can increase the creep parameters (Houde et al. 1987; Bissonnette et al. 2007). For example, Houde et al. (1987) reported that the use of polypropylene fibers can increase creep between 20%
and 40%. Other studies found that creep can be enhanced when fibers with elastic modulus far greater than that of the plain concrete are used, while fibers with elastic modulus lower than that of plain concrete can increase creep (Zhao et al. 2016).

Many test setups and methodologies have been developed to evaluate and/or compare static and dynamic compressive, tensile, and flexural creep of cementitious materials made with and without fibers such as (Bernard 2010; Garcia-Taengua et al. 2014; Arango et al. 2012; Tailhan et al. 2013; Higgins et al. 2013; Wei et al. 2018; Narintsoa et al. 2013; Babafemi and Boshoff 2016; Liang and Wei 2019; Suryanto et al. 2013). The compressive creep test is most commonly used; however, the surface-to-volume ratio of test specimens is greater in flexural creep testing compared to compressive and tensile creep testing (Wei et al. 2013). This is due to the fact that flexural creep ratio of unsealed/sealed condition ranged between 1.75 and 2.0 while this ratio ranged between 1.25 and 1.5 for compressive creep (Wei et al. 2013). Moreover, the flexural creep where members are subjected to bending, represents the actual stress state in concrete beams and slabs (Wei et al. 2013); i.e., concrete members can be subjected simultaneously to tension and compression.

The cracking sensitivity of SCC can be enhanced by the addition of fibers. Fiber-reinforced self-consolidating concrete (FR-SCC) combines the properties of SCC and fibers. Several studies have been carried out to investigate the flexural creep of concrete made with and without fibers. However, limited studies have been carried out on deferred bending (flexural creep) of FR-SCC (Abrishambaf et al. 2015; Buratti and Mazzotti 2012).

To the best knowledge of the authors, data on time-dependent bending behavior of FR-SCC made with expansive agents (EA) that are used to mitigate shrinkage are very limited. The cracking potential of FR-SCC subjected to restrained shrinkage was reported to be moderate, as per ASTM C1581 (2020). Such rating can be enhanced to low by the incorporation of an EA (Kassimi and Khayat 2019). The internal expansion (generally <0.1%) occurs during the first 7 days and can decrease the risk of cracking, as long as tensile stresses resulting from the early-age expansion are lower than the tensile strength of the matrix (Aïtcin and Flatt 2016). The expansion reduces the long-term total shrinkage and hence the risk of cracking, which affects durability (Aïtcin and Flatt 2016). Hence, an adequate repair material exposed to tension under long-term flexural creep should have minimum shrinkage and creep parameters to attenuate the risk of cracking and maintain high performance under serviceability conditions. In most studies dealing with flexural creep, small dimensions were considered, and the flexural creep was mostly tested up to a medium term of less than 90 days.

In this study, fibers were combined with EA in SCC to evaluate the time-dependent behavior of the FR-SCC. This combination was used to mitigate flexural creep of concrete. The flexural response was monitored up to 19 months. The sustained load was applied gradually from low to high levels and from pre- to post-cracking serviceability loads. The gradual creep was followed by gradual creep recovery to evaluate the recovery (reversibility) degree of deflection, deformations, and crack width of the beam members. For representative-purpose, adequate dimensions of 130×180×1800 mm were chosen for the beams. The representative size of tested elements would contribute in enhancing modeling of flexural creep of concrete. Steel frames that can amplify the loads up to 100 times were used to avoid testing of real-scale beams. These frames can carry many superposed concrete beams simultaneously to avoid the use of several separate frames. To evaluate the range of structural performance, various mixture types were prepared including plain SCC, FR-SCC with and without EA, fiber-reinforced self-consolidating mortar (FR-SCM), and fiber-reinforced conventional vibrated concrete (FR-CVC). The study parameters were the mixture type (SCC vs. CVC), fiber type (steel and synthetic), fiber volume (0.5% in concrete and 0.8% in mortar), incorporation of EA, and effect of coarse aggregate.

2. Experimental program

2.1 Materials

Continuously-graded natural sand was used. Crushed limestone aggregates with nominal maximum aggregate size (MSA) of 10 and 20 mm were used for the self-consolidating mixtures (SCC and FR-SCC) and FR-CVC, respectively. The particle-size distributions of the aggregates are in compliance with CSA A23.1 Standards (CSA-A23.1/A23.2 2014). A Type GU cement and ternary cement (CSA GU-b-SF) containing approximately 70% Type GU cement, 25% granulated ground blast furnace slag, and 5% silica fume, by mass of binder, were employed for the FR-CVC and self-consolidating mixtures (SCC, FR-SCC, and FR-SCM), respectively. A powder calcium oxide-based EA was employed as a partial replacement of binder in one of the FR-SCC mixture. The EA content was 6% of mass cementitious materials.

A polynaphthalene sulphonate (PNS)-based high-range water-reducing admixture (HRWRA) with compatible viscosity-modifying admixture (VMA) and liquid solution of sulfonated fatty acids air-entraining admixture (AEA) were incorporated. Two types of fibers were used, including a kinked multifilament polypropylene (KMP) fiber and a hooked-end steel (HES) fiber. The main characteristics of the materials used in this study are presented in Table 1.

2.2 Mixture proportioning

The mixture proportioning of the investigated mixtures is reported in Table 2. The mixtures codification identifies the mixture type (SCC, CVC, or SCM), fiber type...
(KMP or HES), and use of an EA. Compared to the reference SCC, the FR-SCC mixtures necessitated a reduction in coarse aggregate content to maintain the same thickness of mortar covering the fibers and coarse aggregates, thus securing similar workability (Khayat et al. 2014). The FR-CVC mixture was prepared with a water-to-binder ratio of 0.50 that is economical and usually used in the concrete industry. This ratio was 0.43 for the self-consolidating mixtures (SCC, FR-SCC, and FR-SCM).

2.3 Mixing
The mixtures were prepared using a drum mixer with 110-L capacity rotating at 20 rpm. The HES fibers were mixed for 1 min with the sand, coarse aggregates, and the AEA that was diluted with part of the mixing water. For mixtures containing the KMP fibers, the fibers were first mixed with the coarse aggregates and sand for 4 min to break down the fibrillates. This was done before the incorporation of the AEA with part of the mixing water to avoid excessive mixing duration that can affect air volume. The ternary cement (and EA, if used) was then added and mixed for 30 s, followed by the HRWRA and the remaining mixing water. After 1 min of mixing, the liquid-based VMA was introduced, and the concrete was mixed for an additional 2 min. The mixture temperature during mixing and testing was approximately 20°C. The same mixing procedure was applied for the SCC, FR-SCM, and FR-CVC mixtures. The dosage of the AEA was adjusted in order to secure an initial fresh air volume of 7% ± 2%.

2.4 Test methods
The unit weight and air volume were evaluated in accordance with ASTM C138 (2020) and ASTM C231 (2020). The slump test for the FR-CVC mixture was carried out according to ASTM C143 (2020). The slump flow diameter, visual stability index (VSI), and T50 spread time were evaluated (ASTM C1611 2020). The passing ability was determined using the V-funnel, standard and modified J-Ring (Khayat et al. 2014; ASTM C1621 2020), and standard and modified L-box (Khayat et al. 2014) test methods. The clearance between proximate bars in the modified J-Ring and L-box devices were nearly 2.5 times the fiber length. The J-Ring setup employed with the fibrous mixtures made with the HES fibers had only eight bars, giving a clearance of 105 mm between adjacent bars, compared to 42.9 mm employed in the conventional J-Ring device (ASTM C1621 2020) that contains 16 bars. In the case of mixtures made with KMP fibers, six bars were used with a clear spacing of 140 mm. Unlike the regular L-box setup used for SCC that had three blocking bars, a single bar was used in the case of the fibrous mixtures.
The beams used for flexural creep testing measured 130×180×1800 mm (w×h×L). To prevent cracking due to entrapment and enhance surface quality, the V-funnel test with bottom outlet dimensions of 65×75 mm was used for all investigated mixtures. A caisson filling capacity test was used (AASHTO T 349 2013). A modified Tattersall two-point workability rheometer (MK III model) with a vane was used to determine the yield stress ($\tau_y$) and plastic viscosity ($\mu_p$).

In total, 18 beams measuring 130×180×1800 mm (w×h×L), 156 cylindrical specimens measuring 100×200 mm, and 12 prismatic specimens measuring 75×75×285 mm were prepared. The compressive strength ($f'_c$) (ASTM C39 2020), splitting tensile strength ($f'_{st}$) (ASTM C496 2020), and elastic modulus ($E_c$) (ASTM C469 2020) were determined at different ages up to 182 d, and drying shrinkage ($\varepsilon_{dr}$) (ASTM C157 2020) was monitored for approximately 13 months.

Specimens made with FR-CVC were consolidated according to ASTM C192 (ASTM C192 2020). Table 3 summarizes the methods employed for mechanical consolidation of the concrete used for the evaluation of workability and for molding test samples to determine mechanical properties, shrinkage, and creep. Any mechanical consolidation was applied for workability testing and molding test samples for the SCC and FR-SCM mixtures.

Test specimens were cured in the laboratory at ambient temperature and covered with plastic sheets for 24 hrs (ASTM C192 2020). The beams and cylinders were then demolded and covered with wet burlap and plastic sheets for 6 d. The samples were then transferred to a temperature-and humidity-controlled room at 23 ± 2°C and 50% ± 4% RH until the end of testing. After demolding for 24 hrs, the prisms were cured in lime-saturated water for 6 d and then transferred to the controlled room at 23 ± 2°C and 50% ± 4% RH with their corresponding beams. At this time (7 d), the $\varepsilon_{dr}$ and creep testing was initiated.

### 2.5 Beam preparation

The beams used for flexural creep testing measured 130×180×1800 mm (w×h×L). To prevent cracking due to entrapment, two No. 10M ($d_e = 11.3$ mm) reinforcing steel bars were placed in the tension zone for each beam (Fig. 1(a)). Six steel creep frames were prepared, each able to have four superposed beams. Two beams were superposed and loaded symmetrically on the steel frame, as illustrated in Figs. 1(b) and 1(c). A third beam was placed on two supports with the same span as in the loaded beams without any sustained loading to monitor the various responses under self-weight. The beams were tested under four-point bending test, as indicated in Fig. 1. Before applying the loads, the frames were calibrated using a 180-kN capacity load cell equipped with strain-gauge conditioner and voltmeter. The load cell was first subjected to three cycles of compressive load to find a correlation between the applied load (kN) and electrical potential (volt). A relationship with a correlation coefficient (R²) of 0.999 was established. The load cell was then used at the same position of the two superposed beams onto the frame and subjected to three loading cycles for each position 1 to 4 (Fig. 1(b)) for each frame to establish a correlation between the sustained mass (kg) and electrical potential (volt) with high accuracy (R² greater than 0.99). A correlation between the sustained mass at each position and applied load onto the beams was then derived. Therefore, the applied load value can be altered by changing the sustained mass or the lever arm at positions 1 to 4 in Fig. 1(b). The proposed creep frame can therefore amplify the transmitted load to the beams by up to 100 times. For example, to apply a load of 30 kN at position 4 (Fig. 1(b)), it is possible to sustain a relatively small mass of 50 kg instead of a sustained mass of 3000 kg in the four-point flexural test device.

### 2.6 Load-, strain-, and deflection-control systems

In order to evaluate the long-term response of the concrete beams, as illustrated in Fig. 1(a), two electrical strain gauges were glued to the longitudinal reinforcing bars at beam mid-span to measure tensile strain. Two other strain gauges were glued to the top surface of the beam at mid-span to measure concrete compressive strain. The mid-span deflection ($\delta$) measurements over...
a: Two strain gauges for concrete $\varepsilon_c$ for each beam.
b: Two lateral pins for mid-span deflection $\delta$ for each beam.
c: Two strain gauges for steel reinforcement $\varepsilon_s$ for each beam.
d: Rigid steel frame basis as reference for mid-span $\delta$.
e: rigid steel roller comprised between two rigid u-shaped steel plates.

Fig. 1 Beam and frame configurations: (a) symmetrical load-, strain-, and deflection-control systems; (b) 3D steel frame setup with beams loaded under four-point flexural creep test; (c) creep frame setup with loaded and unloaded beams.

Notes: Dimensions in mm. Lateral and bottom cover over steel reinforcement was 20 mm, as shown in Fig. 1 (a).
...on opposite two faces of the beams. A high precision magnifying telescope (±0.01 mm) was used to evaluate crack widths \( (w_c) \) along the vertical faces of the beams, which was determined in the constant moment zone (between the two concentric applied loads) of the flexural beams. For each mixture type, creep flexure deformation and cracking development were monitored for the two tested beams, and mean values were considered in the analysis.

Each frame was gradually loaded through four pre-and post-cracking levels (1 to 4 corresponding to suspended loads of 5 to 30 kN, respectively. This was done by changing the value and/or the position of a mass placed on a rigid metallic plate sustained from 1 of the 4 positions along the secondary lever arm, as shown in Fig. 1(b).

Table 4 presents the load levels used for creep/recovery process over time. The total duration of creep and recovery testing was approximately 19 months. The creep measurements started at the end of the moist curing (age of 7 d) and continued up to age of 420 d (duration of 413 d). Creep testing was followed by gradual creep recovery from age of 413 d to 469 d (duration of 49 d).

The highest creep load of 30 kN corresponding to load level 4 was applied for all beams, except for those made with the SCM-HES-0.8 mixture where the beams underwent recovery after this stage. The creep frame used for the SCM-HES-0.8 mixture was loaded up to the third level (23 kN) to prevent yielding of the reinforcing steel. As can be seen in Table 4, the maximum applied \( M_{u/d,cr} \) value was only 0.71\( M_{u/cr} \) value to prevent damage of the frame equipment after observing excessive \( \delta \) and strain in concrete \( \varepsilon_c \), guarantee the reinforcement effectiveness with applied load lower than yield load, thus allow recovery.

After the gradual creep loading, the undamaged beams were then gradually unloaded to the same set of load levels to evaluate the degree of creep recovery (reversibility).

3. Experimental results and discussion

3.1 Workability

As indicated in Table 5, the investigated self-consolidating mixtures achieved high fluidity levels with slump flow values greater than 650 mm. The mixtures exhibited high stability with a VSI ranging between 0 and 1. Excellent filling capacity (caisson test) of 84% to 100% was obtained for the self-consolidating mixtures. The \( \tau_0 \) and \( \mu_p \) values ranged between 40 and 59 Pa and 7 and 16 Pa.s, respectively.

3.2 Mechanical properties and drying shrinkage

As indicated in Table 6, the self-consolidating mixtures had at 180-d \( f'_c \) values ranging between approximately 50 and 60 MPa and \( f'_{sp} \) between 4.7 and 7.7 MPa with a minimal \( f'_{sp} \) value for the plain SCC mixture. The self-consolidating concrete mixtures had an average 180-d \( E_c \) of 31 GPa. A lower \( E_c \) value of 23.8 GPa was obtained for the FR-SCM given the absence of coarse aggregate. The CVC-HES-0.5 and SCC-HES-0.5 mixtures had the highest \( E_c \) values of 32.3 and 31.8 GPa, respectively, due to the highest coarse aggregate contents of 1013 and 791 kg/m³, respectively.

Drying shrinkage \( (\varepsilon_{sh}) \) testing started after 7 d of moist curing. The \( \varepsilon_{sh} \) of the SCC made with and without fibers after 390 d of testing ranged between 810 and 1050 \( \mu \)strain versus 700 \( \mu \)strain for the reference FR-CVC. The highest \( \varepsilon_{sh} \) of 1360 \( \mu \)strain was obtained for the FR-SCM mixture given its highest paste volume of 58% vs. 34% to 45% for the remaining mixtures and...
The FR-SCC mixtures had 11% to 24% greater $f'$c and 17% to 64% greater $f'_s$ than the reference SCC mixture. The $Ec$ was ±5% compared to that of the reference SCC mixture. The FR-SCC mixtures had εdr with a spread of -17% to 7% compared to the SCC mixture. The incorporation of the EA in the SCC-KMP-0.5-EA mixture increased the $f'$c, $f'_s$, and $Ec$ by 2%, 13%, and 5%, respectively, and reduced εdr by 19%. This shows the synergistic effect when fibers and EA are combined. The incorporation of EA led to shrinkage compensation of the SCC-KMP-0.5-EA mixture that developed 13% and 36% less εdr after 1 and 7 d, respectively, compared to the SCC-KMP-0.5 mixture. The FR-SCM mixture had 7% increase in $f'$c, 45% in $f'_s$, 39% in εdr, and 22% decrease in $Ec$ compared to the reference SCC mixture.

### 3.3 Flexural creep

The structural performance of the investigated beams was evaluated based on the results obtained and presented in Figs. 2 to 5. The responses considered were the mid-span δ, εc, εs, and $w_{cr}$. The main results at different ages are depicted in Table 7. Figure 2 shows the evolution of the mid-span δ over time, of the six sets of beams, under gradual increased load for the flexural creep tests. The long-term $\varepsilon_c$ and $\varepsilon_s$ values measured under multi-level flexural creep testing are plotted in Figs. 3 and 4, respectively. Figure 5 illustrates the development of the $w_{cr}$ at the constant moment of beams.
Table 6 Mechanical properties and shrinkage results.

| Property       | $f'c$ (MPa) | $f'sp$ (MPa) | $E_c$ (GPa) | $\varepsilon_{dr}$ (µstrain) |
|----------------|-------------|---------------|-------------|-----------------------------|
| Age (d)        |             |               |             |                             |
| CVC-HES-0.5    | 22.0        | 32.2          | 34.1        | 34.9                        |
| SCC            | 31.0        | 41.2          | 47.2        | 48.0                        |
| SCC-KMP-0.5    | 36.0        | 47.1          | 47.7        | 49.1                        |
| SCC-KMP-0.5-EA | 29.6        | 43.5          | 48.0        | 57.8                        |
| SCC-HES-0.5    | 40.9        | 55.7          | 58.5        | 59.7                        |
| SCM-HES-0.8    | 32.8        | 47.1          | 49.5        | 51.5                        |

Table 7 Flexural creep parameter values.

| Response       | $\delta$ (mm) | $\delta$ (µm/MPa) | $\varepsilon_c$ (µstrain) | $\varepsilon_s$ (µstrain) | $w_{cr}$ (mm) |
|----------------|---------------|--------------------|---------------------------|---------------------------|----------------|
| Age (d)        |               |                    |                           |                           |                |
| CVC-ST-0.5     | 4.5           | 5.5                | 3.1                       | 305                       | 357            |
| SCC            | 5.2           | 6.7                | 3.8                       | 360                       | 357            |
| SCC-KMP-0.5    | 5.0           | 6.3                | 3.9                       | 353                       | 357            |
| SCC-KMP-0.5-EA | 3.9           | 5.0                | 3.4                       | 272                       | 357            |
| SCC-HES-0.5    | 4.3           | 5.1                | 3.2                       | 296                       | 357            |
| SCM-HES-0.8    | 8.1           | --                 | 6.5                       | 617                       | 357            |

Notes:
- From the beginning of creep testing at 7 d of age.
- Age corresponding to level 3 (23 kN) in Table 4.
- Age corresponding to the maximum loading level 4 (30 kN).
- Age corresponding to the end of recovery (load level 1 of 5 kN).

Values in Table 7 indicate total values (including time-dependant and elastic values).
Values in parenthesis correspond to cumulative elastic (instantaneous) values due to changes in loading level. Negative values indicate cumulative elastic values obtained after loading and unloading.
N.A: Not available value.
In general, the behavior at mid-span of the investigated beams followed a similar trend for all considered total responses ($\delta$, $\varepsilon_c$, $\varepsilon_s$, and $w_{cr}$) that include the time-dependent and elastic (instantaneous) responses. The analysis below considered the total responses. With the application of each higher creep load level, the values of these responses increased consequently but at different degrees, depending on the mixture type. In general, the $\delta$, $\varepsilon_c$, and $\varepsilon_s$ values of beams made with FR-SCC mixtures with and without EA were lower than the remaining mixtures. The values of beams made with the reference SCC without any fibers and the fiber-reinforced mortar were higher than the remaining mixtures, with the values of the FR-SCM mixture considerably larger than the other mixtures. For the $w_{cr}$, the behavior was different where the curve of SCC was far above those of the fibrous mixtures.

A detailed analysis was undertaken to highlight the effect of fiber inclusion (FR-SCC vs. SCC), fiber type, and use of EA as well as the synergistic effect between fibers and EA (FR-SCC-EA vs SCC) on flexural creep performance of the investigated mixtures, including $\delta$, $\varepsilon_c$, $\varepsilon_s$, and $w_{cr}$ responses. The analysis was also based on the comparison of structural performance of the FR-SCC and FR-CVC mixtures made with the same fiber type and $V_f$. Similarly, a comparison of performance was made between the FR-SCM and the rest of the mixtures, including the FR-SCC mixture made without any EA. The FR-SCM had the highest $\varepsilon_{dr}$ and lowest $E_c$ values enabled the highest total $\delta$ after 357 d of sustained loading, as shown in Fig. 2 and Table 7. The $\delta$ value was 1.6 to 2.1 times that of the remaining mixtures and specifically 1.6 to 1.9 times that of FR-SCC made without EA.

The flexural specific creep, which is the creep strain by unit stress, can be determined using a simplified method based on elastic analysis. The flexural specific creep can be expressed as the compressive stress of concrete corresponding to a given applied load level. The compressive force can be calculated from the theory of moments ($\Sigma M = 0$):

$$M = C \times \left( d - \frac{kd}{3} \right)$$  \hspace{1cm} (1)

where $M$ is moment of flexure that can be deduced from Fig. 1(a), $C$ is compressive force, $d$ is distance from the extreme compression fiber to the centroid of tensile steel reinforcement, and $k$ is an effective length factor.

$$k = \sqrt{\rho n^2 + 2 \rho n - \rho}$$  \hspace{1cm} (2)

where $\rho$ is the reinforcement ratio ($\rho = A_s/A_c$), and $n = E_s/E_c$. The $A_s$ and $A_c$ are areas of tensile steel reinforcement and cross section of concrete, respectively. The $E_s$ and $E_c$ correspond to the elastic moduli of steel reinforcement and concrete, respectively. From Fig. 6, $C$...
can be determined as follows:

\[ C = \frac{1}{2} b \times k d \times f_c \]  

(3)

where \( b \) is the beam width and \( f_c \) is compressive stress. The compressive force \( C \) can also be deduced from Eq. (1) and compared to the expression given in Eq. (3) to deduce the compressive stress \( f_c \) given in Eq. (4):

\[ f_c = \frac{2C}{b \times k d} \]  

(4)

For the example of deflection at 357 d, the flexural specific creep can be calculated by dividing the deflection in \( \mu \text{m} \) by the applied stress in MPa corresponding to the load level of 23 kN. The results are reported in Table 7. The correlation between deflection in mm and specific deflection in \( \mu \text{m}/\text{MPa} \) was very high with \( R^2 \) of 0.9966, as shown in Fig. 7. Therefore, and for simplification, it was decided to perform all strains and deformations (deflection, crack width, strain in concrete and strain in reinforcing steel) in their unit without considering the specific creep since the same loads at a given age were applied for all frames.

### 3.3.2 Concrete and reinforcement strain

As shown in Figs. 3 and 4, the variations of the \( \varepsilon_c \) and \( \varepsilon_s \) with time and loading levels were similar for the various mixtures. The two FR-SCC mixtures (SCC-KMP-0.5 and SCC-HES-0.5) had 20% to 24% lower total \( \varepsilon_c \) and 10% to 24% lower total \( \varepsilon_s \) compared to SCC beams made without any fibers (Table 7). The lowest strain values were observed with beams made with FR-SCC and steel fibers. The use of EA in FR-SCC enhanced the \( \varepsilon_c \) and \( \varepsilon_s \) values by 10% and 12%, respectively. Compared to the reference SCC, these enhancements were 31% and 21%, respectively. This clearly demonstrates the synergistic effect between the fibers and EA.

The deflection strains values of the investigated beams were comparable at different load levels with the reference CVC-HES-0.5 mixture. The SCC-HES-0.5 beams had \( \varepsilon_c \) lower by 22% than that of the CVC-HES-0.5 beams. The CVC-HES-0.5 mixture was proportioned with the lowest paste volume of 34% compared to 41% to 57% of the other mixtures. Furthermore, the mixture had the highest coarse aggregate volume of 37% vs. 0 to 29% compared to the other mixtures. The CVC-HES-0.5 mixture developed the lowest 390-d \( \varepsilon_{cr} \) value of 690 \( \mu \text{strain} \) and the highest \( E_c \) of 32.3 GPa compared to 810 to 1360 \( \mu \text{strain} \) and 23.8 to 31.8 GPa, respectively. The FR-SCM beams had 25% to 81% greater \( \varepsilon_s \) and up to 32% greater \( \varepsilon_c \) than the remaining mixtures. These values were 55% to 64% and 11% to 32%, respectively, greater than the FR-SCC mixtures made without any EA. For all mixtures, no clear correlation was obtained between the \( w_{cr} \) and \( \varepsilon_c \). This was likely due to the fact that the cracks appeared at different locations of the the constant moment zone and not necessarily at the mid-span of beams were the \( \varepsilon_c \) values were determined.

### 3.3.3 Crack width

As expected, the incorporation of fibers significantly increased the through-crack bearing capacity during the flexural creep testing, regardless of the mixture and fiber type, as shown in Fig. 5. The incorporation of fibers in SCC (FR-SCC vs. SCC) reduced the \( w_{cr} \) by 63%. The use of EA in FR-SCC reduced, in turn, the \( w_{cr} \) by 29%. A further reduction of 74% was obtained when the synthesis (KMP) fibers were combined with EA compared to the non-fibrous SCC without any fiber, hence showing the synergy between fibers and EA.

After 357 d of creep testing, the \( w_{cr} \) values of the fibrous mixtures were 63% to 79% lower than that of the non-fibrous SCC. It should be noted that the SCC made without fibers underwent a maximum \( w_{cr} \) of 0.24 and 0.48 mm after 357 and 406 d of creep testing, respect-
tively. The use of fibers and the $V_f$ were the main parameters affecting cracking. For example, the FR-SCM repair material resisted well cracking due to the relatively high $V_f$ of 0.8%, despite its lowest $E_c$ value of 23.8 GPa and highest $\varepsilon_{ck}$ of 1360 ustrain. Despite the high 180-d $E_c$ value of the SCC mixture of 30.4 GPa compared to 23.8 to 32.3 GPa, the SCC mixture had the largest $w_{cr}$ value of 0.24 mm compared to 0.05 to 0.09 mm for the fibrous mixtures, thus indicating the effect of fibers on crack opening.

The FR-SCC beams made with HES fibers had 75% higher $w_{cr}$ compared to the FR-CVC mixture made with the same fiber type and $V_f$. This can be due to the difference in composition, such as coarse aggregate content of 750 vs. 1013 kg/m², water-to-binder ratio of 0.43 vs. 0.50, relative paste volume of 45% vs. 34%. However, the addition of EA in the FR-SCC enabled similar $w_{cr}$ to the FR-CVC mixture. Comparing the fibrous mixtures, the FR-SCM mixture resulted in 9% lower $w_{cr}$ compared to the FR-SCC mixture made without EA and 60% higher $w_{cr}$ compared to the FR-CVC mixture. This demonstrates the benefit of FR-SCM in resisting cracking when a mortar has to be used for thin repair sections.

### 3.4 Flexural creep recovery

As mentioned earlier, the gradual increase in flexural creep was followed by gradual decrease in loading resulting in creep recovery. The variations of the mid-span $\delta$, $\varepsilon_s$, $\varepsilon_c$, and $w_{cr}$ with time of the six sets of beams are illustrated in Figs. 2 to 5. Similar variations of the various responses were observed for all tested beams. A similar spread of the response values found during the multi-level creep testing was obtained during the multi-level creep recovery. The creep recovery responses were not totally reversible since the $\varepsilon_c$ and $\varepsilon_s$ were close to the yield limits of 2% and 3% ustrain, respectively. It is to be noted that the maximum applied moment ($M_n$) reached a level of 4.2 $M_o$ to 2.3 $M_o$ (0.53 $M_o$ to 0.71 $M_o$) at load level 4 for the concrete mixtures and load level 3 for the FR-SCM, as indicated in Table 4.

#### 3.4.1 Deflection

As noted in Fig. 2 and Table 7, the gradual creep recovery between the highest load level 4 (30 kN) after sustained loading for 406 d and the lowest load level 1 (5 kN) after a loading duration of 462 d was accompanied by 20% to 44% recovery of $\delta$ for the tested beams. The lowest $\delta$ recovery value was obtained with the SCM-HES-0.8 mixture despite the shorter loading duration of 357 d and lower applied loading level 3 of 23 kN (instead of 462 d and 30 kN for the other mixtures). This was due to the lowest $E_c$ of the SCM-HES-0.8 material compared to the remaining mixtures (180-d $E_c$ of 23.8 GPa vs. 29.3 to 32.3 GPa for the other mixtures). It should be noted that the $\delta$ values for the FR-SCM and the other concrete beams following complete unloading were 6.5 and 3.1 to 3.9 mm, respectively. In contrast, the highest $\delta$ recovery value was obtained with the CVC-HES-0.5 mixture due to its highest $E_c$ compared to the remaining mixtures. The range of $\delta$ recovery for the FR-SCC mixtures was 36% to 38%. Neither the use of fiber or EA or fiber type affected the range of $\delta$ recovery.

#### 3.4.2 Concrete and reinforcement strain

From Figs. 3 and 4, and Table 7, the recovery of the $\varepsilon_c$ values between the maximum loading level (4 or 3 depending on mixture type) and the end of the creep recovery period varied between 16% and 31%. The values were 39% and 69% for the $\varepsilon_c$. The lowest and highest values of strain recovery for the $\varepsilon_c$ and $\varepsilon_s$ values were obtained with the SCM-HES-0.8 and CVC-HES-0.5 mixtures for the same reason for $\delta$. The range of $\varepsilon_c$ and $\varepsilon_s$ recovery for the FR-SCC mixtures was 25% to 31% and 43% to 69%, respectively. As in $\delta$, the incorporation of fibers and EA did not affect the range of strain recovery; however, the use of KMP fibers increased the strain recovery for the $\varepsilon_c$ by 6% and 26%, respectively.

#### 3.4.3 Crack width

As shown in Fig. 5 and Table 7, at the end of the creep recovery testing, the recovery range in $w_{cr}$ was 31% to 68% compared to the maximum $w_{cr}$ registered during creep testing. Similarly to the case of $\delta$, $\varepsilon_c$, and $\varepsilon_s$, it was found that the lowest and highest values of $w_{cr}$ recovery were obtained with the SCM-HES-0.8 and CVC-HES-0.5 mixtures. The recovery range of $w_{cr}$ for the FR-SCC mixtures was 58% to 60%. The recovery range in $w_{cr}$ was not affected by the use of fiber or EA and fiber type.

In this analysis, the bridging effect of the fibers along the crack surfaces on flexural behavior and the time-dependent characteristics were not considered. Future research necessitating the consideration of the bridging effect of fibers at the crack surface and the time-dependency of the bridging effect on the flexural behavior of the reinforced concrete beam using fiber-reinforced concrete is recommended.

### 3.5 Overall performance

The overall structural performance under flexural creep testing was evaluated at a post-cracking level (23 kN) after 357 d creep testing using the star-plot approach where close-loop areas of the star-plot correspond to the performance of a given mixture. The overall performance for the flexural creep tests is based on the mid-span $\delta$, $\varepsilon_c$, $\varepsilon_s$, and $w_{cr}$ values. Restrained shrinkage values from the ring test (ASTM C1581 2020) were also considered to evaluate the overall performance of the investigated mixtures. At the age of 24 hrs, the outer ring was removed, and the samples were moist-cured for 2 d under wet geotextile covered with polyethylene sheet. At the age of 3 d, the top surfaces of the concrete ring specimens were sealed with adhesive aluminum-foil tape, and the lateral mixture surfaces were air-cured at 23 ± 2°C and 50% ± 4% RH. The response parameters include the time to cracking ($\varepsilon_{cr}$), $w_{cr}$, micro deformation in the steel ring, as well as sealed ($\varepsilon_{se}$) and unsealed ($\varepsilon_{un}$).
shrinkage values. The results of the restrained shrinkage that are considered here correspond to values reported by the authors for the same mixtures that were tested for flexural creep (Kassimi and Khayat 2019).

The comparison of the relative performance under flexural creep and restrained shrinkage is presented in Fig. 8. Weighted factors of 2, 3, 1, and 3 were assigned to $\delta$, $\varepsilon_c$, $\varepsilon_s$, and $w_{cr}$, respectively. These factors consider the relative importance of the various performance metrics that are critical for repair applications. The branches of the star diagram were set so that high values reflect better performance for each of the considered responses. Therefore, the highest $t_{cr}$ value and the lowest $\varepsilon_{se}$, $\varepsilon_{un}$, ring $\mu$strain, $w_{cr}$, $\delta$, $\varepsilon_c$, and $\varepsilon_s$ values that indicate desirable performance correspond to the highest branch values and vice versa. The branch values range from 0 to 1 (0 to 100%×1), from 0 to 2 (0 to 100%×2), or from 0 to 3 (0 to 100%×3) for properties weighted with factors of 1, 2, or 3, respectively. For example, Table 7 shows that the $\varepsilon_s$ for the SCC-HES-0.5 mixture using the flexural creep test is 1095 µstrain, which is the lowest value compared to the SCC, FR-SCC, and FR-SCM mixtures. This value indicates the best desirable performance, thus corresponding to 1 (or 100%×1 on a scale of 0 to 1) on the star branch scale, as shown in Fig. 8. The $\varepsilon_c$ value for the same mixture is 2.39 on a scale of 0 to 3 (because the weighting factor is 3). This value of 2.39 represents a relative value compared to the minimum and maximum $\varepsilon_c$ for all mixtures presented in Table 7. For the same SCC-HES-0.5 mixture, the 2.57 and 1.80 values for the $w_{cr}$ and $\delta$, respectively, on scales of 0 to 3 and 0 to 2, respectively, were calculated using the same approach.

For each test (flexural creep and restrained shrinkage), a close-loop area of the star-plot of each mixture was calculated following the same approach and then divided by that of the SCC beams to deduct relative performance values. A greater star-plot area corresponds to a better overall performance.

The relative overall performance of the investigated mixtures under flexural creep varied between 0 and 9.3 times compared to the reference SCC. The relative overall performance under flexural creep of the SCC-HES-0.5 mixture was 43% higher than that of the SCC-KMP-0.5 mixture. The incorporation of EA increased the relative overall performance of the FR-SCC made with synthetic fibers by 77%. The overall performance of the FR-SCM was low compared to the concrete mixtures. The relatively low $E_c$ affected the overall performance of the FR-SCM, but it is not the only parameter affecting the creep response. SCC with the same range of $E_c$ as that of FR-SCC had the lowest performance due to the absence of fibers. Therefore, fibers and $E_c$ have significant effect on enhancing the overall performance.

In the case of restrained shrinkage, the relative overall performance of the investigated mixtures ranges between 0.6 and 7.3 times compared to the reference SCC. The use of EA improved the overall flexural performance by 3.8 times. The flexural creep and restrained shrinkage tests delivered similar relative performance ranks for the fibrous and SCC mixtures. The rank ranged between 5.3 to 7.6 times vs. 1.9 to 2.4 times for the FR-SCC, 9.3 times vs. 7.3 times for the FR-SCC made with EA and synthetic fibers, and 0.5 times vs. 0.6 times for the FR-SCM mixture. Both the restrained shrinkage and flexural creep tests were beneficial in comparing the performance ranking of the investigated mixtures, although the testing duration of the former test was considerably lower.

From Fig. 8, it can be seen that the relative performance of a given mixture in the two sets of differed flex-

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Fig. 8 Overall performance under four-point flexural creep test and restrained shrinkage using ring test of fiber-reinforced mixtures.
(Notes: In restrained shrinkage, $t_{cr}$: time-to-cracking; $w_{cr}$: crack width; $\mu$strain: deformation of the steel-ring; $\varepsilon_{se}$: sealed shrinkage; $\varepsilon_{un}$: unsealed shrinkage).
ure (flexural creep) and restrained shrinkage was not at the same level, but the two tests enabled similar tendency and ranking. In all cases, the FR-SCC-EA mixture yielded the highest overall performance followed by the FR-SCC mixtures.

4. Conclusions

Long-term flexural creep testing was carried out on beams mounted on rigid steel frames equipped with suspended loading configurations to allow for sustained four-point bending creep testing. Six repair materials were tested, including SCC and FR-SCC designated for repair of concrete structures and FR-SCM that can be used for thin structural repairs. A long-term creep testing followed by creep recovery was carried over 19 months. Comparisons of the mixture performance were made under time-dependent and cracking potential using the restrained shrinkage. The study aimed at evaluation of performance of FR-SCC combined with EA to reduce the creep parameters, compared with other mixture types. Based on the results discussed in this study, the following conclusions can be drawn:

1. A novel test method was employed to evaluate the creep of concrete beams under different levels of sustained loading and subsequent creep recovery. The test enabled the evaluation of long-term deflection under different levels of stress, such as service loads of uncracked samples. This method allows testing superposed beams on one frame, hence avoiding the use of many test setups. This method allows the use of representative (medium-scale) elements that reduces scale error in test results. Moreover, it permits the amplifying of the applied load by up to 100 times, hence reducing of the magnitude of sustained loads and the volume of test samples.

2. The restrained shrinkage test provided similar performance ranking of the investigated repair mixtures to the ranking deduced from the flexural creep test.

3. The addition of fibers in FR-SCC increased mechanical properties and decreased structural response ($\delta$, $\varepsilon_s$, $\varepsilon_c$, and $w_{cr}$) by up to 65% compared to non-fibrous SCC. The use of fibers led to approximately eight times improvement in the overall performance under flexural creep testing. Steel fibers in FR-SCC yielded approximately 45% better overall performance compared to synthetic fibers.

4. The use of EA in FR-SCC made with synthetic fibers decreased $\varepsilon_{cr}$ by up to 20%. It also increased mechanical properties and decreased structural responses ($\delta$, $\varepsilon_s$, $\varepsilon_c$, and $w_{cr}$) by up to 15% and 30%, respectively. The EA led to 80% improvement in the overall performance of concrete subjected to long-term deflection. This improvement was nine times that of SCC without fibers.

5. The best performance under flexural creep in ascending order was obtained with the FR-SCC made with EA, followed by FR-SCC without EA, then SCC and FR-SCM.

6. The FR-SCC and FR-SCM mixtures subjected to flexural creep had crack widths of up to 0.19 mm compared to 0.48 mm for the SCC mixture. The FR-SCM mixture exhibited high resistance to cracking despite the relatively high $\varepsilon_{cr}$, $\varepsilon_s$, and $\varepsilon_c$ values and low $E_c$.

7. Despite of some creep recovery, a residual deformation was observed for beams subjected to a loading level that had exceeded the cracking load. The creep recovery can lead to a reduction of mid-span $\delta$, $\varepsilon_s$, $\varepsilon_c$, $w_{cr}$ of 15% to 70%. The recovery degree was dependent on $E_c$ value of the repair material and was independent on the use of fiber and EA and fiber type, except for the degree of recovery of the $\varepsilon_s$ and $\varepsilon_c$ values that are influenced by the fiber type.

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