Research paper

Development of Strain-Induced Stresses in Early Age Concrete Composed of Recycled Gravel or Sand

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Abstract

This paper aims at identifying the effect of the substitution of natural coarse gravel and sand by recycled gravel and sand on the early age development of the volume change and the mechanical properties since setting. For this purpose, a new experimental testing protocol for the characterization of cementitious materials at early age is used. This new approach is based on the repeated application of thermal variation and loading using a newly developed testing device. The high porosity and absorption of the recycled aggregate and sand induce a strong reduction of the autogenous deformations, the modulus of elasticity and the strength during the hardening process. A significant increase of the basic creep phenomenon is observed when using recycled aggregate, especially with recycled sand and at very early age. An elastic and viscoelastic calculation of the restraint of the free deformations shows that the use of recycled gravel and sand decreases the risk of cracking in sealed condition.

1. Introduction

Aggregates, which are the backbone of concrete, are inequitably distributed resources and far from inexhaustible. They represent generally between 60 and 75% of the concrete volume. Their transport is very energy intensive and it is therefore necessary to use local resources to reduce the environmental impact of the very huge production of concrete in the world. One part of the solution to this problem is the use of recycled aggregate instead of natural aggregate. It is thus expected that recycled aggregate reduces CO2 emission, energy consumption and the needs in natural raw materials. However, their availability and their quality cannot be ensured (Dhir et al. 2019a, 2019b). Therefore, recycled aggregates are only one part of the solution for the replacement of natural aggregate.

The European directive 2008/98/EC states that in 2020 more than 70% of the construction waste must be reused or recycled. Many studies were already performed on the recycled aggregate and are related to the technologies and processes of production of the recycled aggregate, e.g., crushing process and selective sorting technology (Dhir et al. 2019c; Park et al. 2018; Pedro et al. 2014), their influence at the concrete and structural scale, e.g., fresh properties, mechanical performance and durability (Mani 2014; Yehia et al. 2015; Zhao et al. 2015), and to the sustainable development (Behera et al. 2014; Dosho 2007; Levy and Helene 2004; Tam et al. 2018). Several projects related to these 3 subjects were carried out during the last decades in several countries e.g. RESIBA in Norway (Karlsen et al. 2002), CalRecycle in USA (DOT 1993) and NeReMa in Finland (Kuosa 2012). However, still, only a part of the materials of deconstructed concrete is reused (Tam et al. 2018). In order to change this trend, the French National Project for research and development “Recybeton” (Irex 2018) has been launched in order to re-use all the concrete coming from construction waste for the production of new concrete or hydraulic binders.

For structural applications, the use of these "green" materials requires a complete characterization of the evolution of the physical and mechanical properties which are quite different from those of standard concretes. Several properties of the aggregate affect the concrete properties such as the particle size distribution, shape, nature, porosity and initial water saturation. Therefore the replacement of natural aggregate by recycled aggregate influences the short and long term performance of concrete. Studies concerning recycled concrete focus mainly on the long term properties. As indicated by Marinkovic et al. (2010), it was generally observed that the replacement of natural aggregate by recycled one reduces the concrete density, the mechanical performance (decrease of the compressive strength, tensile strength, elastic modulus and abrasion resistance and increase of the creep) and the freezing and thawing resistance and increases the drying shrinkage.

To ensure the durability of concrete structures, it is also necessary to know the short-term development of the mechanical and chemical properties of cementitious materials. At early age, the development of the free deformation induced by desiccation (drying shrinkage) and hydration (thermal and autogenous deformation) are generally partly or fully restrained which leads to the development of internal stresses. For concrete structures, the evolution of the restrained strains and the associated
stress development depend on the type of structure (thin or massive), the exposure of the structure to the environment (e.g. sealed by the formwork or exposed to drying) and the composition of the concrete (e.g. type of cement, W/C). These stresses can cause cracking in the concrete structure. Figure 1 illustrates how the cracking sensitivity of a massive structure is defined (Delsaute et al. 2017). The free deformations of the material after setting are mainly composed by the autogenous deformation \( \varepsilon_{\text{a}} \) and the thermal deformation \( \varepsilon_{\text{th}} \). The thermal deformations are function of the evolution of the temperature inside the concrete material and the evolution of the coefficient of thermal expansion \( \alpha _{\text{CTE}} \) of the concrete. For massive concrete structure, two stages are observed: (i) just after setting, a large amount of heat is produced by the hydration reaction, which leads to an increase of the temperature inside the cement paste and thus to an increase of the thermal strain. As a result, a swelling of the concrete takes place, (ii) when the heat of hydration decreases, both autogenous and thermal strains decrease and a global shrinkage occurs. For the determination of the stress under restrained condition, the developments of the elastic and viscous properties are important parameters. In addition, the degree of restraint of the concrete element must be considered for the stress calculation. During the heating period, the concrete element is mainly in compression and inversely during the cooling period the concrete is submitted to tension. In order to avoid cracking, the stresses must not exceed the concrete strength.

This paper focuses on the effect of the substitution of natural gravel and sand by recycled gravel and sand on the short-term development of concrete properties at early age. Crushed aggregate coming from the recycling of demolition concrete are used in this study. Based on the development of the free deformation (autogenous and thermal deformation) and the mechanical properties (strength, elastic and creep properties), an estimation of the impact of recycled aggregate on the risk of cracking induced by the restrained of the free deformation in sealed conditions corresponding to the case of a massive structure is carried out. The paper is structured in 4 sections (apart from the present introduction), concerning respectively: materials and methods (section 2), experimental results (section 3), evolution of the stress under restrained conditions (section 4), as well as the conclusions (section 5). This study aims to highlight the interest of the use of recycled aggregate for concrete structures. This paper is an extended and enhanced version of the work originally titled ‘Influence of recycled aggregate and recycled sand on the development of the early age properties of concrete since setting’ reported in the SynerCrete’18 International Conference on Interdisciplinary Approaches for Cement-based Materials and Structural Concrete (Delsaute and Staquet 2018).

2. Materials and methods

2.1 Concrete compositions

The substitution of natural aggregate by recycled aggregate is studied on four concretes for which mix proportions are given in Table 1. Each composition was defined in the frame of the French National Project “Recybeton” (Irex 2018). For each composition, the effective water-to-equivalent binder ratio and the volume fraction of aggregate are the same. The content of cement, limestone filler and superplasticizer varies slightly in order to obtain a same workability (class S4). Trial batches were performed to adjust their content. Concrete are referred by XRSYRA where X and Y are the percentage of replacement of natural sand and natural gravels by recycled sand (RS) and recycled gravels.
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Table 1 Mixture proportions in kg/m³ and materials properties of the concrete compositions (Bendimerad et al. 2016a, 2016b).

| Composition     | 0RS0RA | 0RS30RA | 0RS100RA | 30RS0RA |
|-----------------|--------|---------|----------|---------|
| Natural gravel  | 6,3/20 | 820     | 462      | 729     |
| Recycled gravel | 10/20  | -       | 296      | 701     |
| Natural gravel  | 4/10   | 267     | 228      | 190     |
| Recycled gravel | 4/10   | -       | -        | 163     |
| Natural sand    | 0/4    | 780     | 813      | 806     |
| Recycled sand   | 0/4    | -       | -        | 235     |
| CEM II/A-L 42.5 | 270    | 276     | 282      | 276     |
| Limestone filler| L      | 45      | 31       | 31      |
| Superplasticizer| SP     | 0.747   | 0.861    | 0.798   |
| Effective water | Weff   | 180     | 185      | 189     |
| Total water*    | Wtot   | 194.6   | 212.3    | 241.0   |
| Wagg            | 14.6   | 27.3    | 52.0     | 36.4    |
| Weff/Beq**     | 0.64   | 0.65    | 0.65     | 0.65    |

* Wtot = Weff + 0.8 x amount of SP (80% of SP mass is water) + water absorbed by the sand and the gravels (Wagg).
** Beq = C + k x L. According to the European standard EN 206/CN, the activity coefficient k = 0.25.

Table 2 Properties of sand and gravel.

| Nature and type | Porosity [%] | Density |
|-----------------|--------------|---------|
| Natural sand    | 0/4          | Alluvial sand - siliceous | 1.2 | 2.6 |
| Recycled sand   | 0/4          | Fine aggregate from the recycling of demolition concrete | 10.65 | 2.1 |
| Natural gravel  | 4/10         | Crushed aggregate - dark limestone | 0.56 | 2.73 |
|                 | 6.3/20       | -       | 0.53     | 2.73 |
| Recycled gravel | 4/10         | Crushed aggregate from the recycling of demolition concrete | 5.3  | 2.34 |
|                 | 10/20        | -       | 4.89     | 2.32 |

(RA) in volume respectively. The first composition, called 0RS0RA, is a reference concrete without recycled aggregate. For the second and third composition, 30 and 100% of the natural gravels are replaced by recycled gravels in volume. These compositions are called respectively 0RS30RA and 0RS100RA. For the last composition 30RS0RA, 30% of the natural sand is replaced by recycled sand in volume. All materials come from the same batch of production. An ordinary Portland cement of type CEMII/A-L 42.5 N was used. Its density and Blaine fineness are 3.09 and 3700 cm²/g. The cement is mainly composed by clinker (83.9%), limestone (10.6%) and gypsum (3.3%). All natural and recycled gravels and sand were used in saturated-surface-dry conditions. The water needed for the saturation of the sand and gravel is defined according to their absorption at 24 hours. For each mix, gravels and sand were saturated 24 hours before the concrete mixing. In Table 1, the mass of sand and gravel per cubic meter of concrete is given in dry condition. The effective water to equivalent binder ratio is around 0.65. The mixing procedure is the same for each concrete mixture. The porosity, rate of absorption and the density of the sand and gravels (natural and recycled) have been previously determined by Bendimerad, et al. (2015) by means of hydrostatic method. The nature, type, porosity and density of natural and recycled sand and gravel are indicated in the Table 2. The porosity of the recycled aggregate is around 10 times higher than the one of the natural aggregate and, inversely, the density of the recycled sand and gravels is respectively 20 and 15% lower than the one of the natural aggregate. In consequence, as aggregates are used in saturated-surface-dry conditions, the total water absorbed by the sand and the gravels (Wagg) is different for each composition. This means that for higher content of recycled gravel/sand the content of water inside the aggregate is higher. More details about the properties of the concrete components are given in (Bendimerad et al. 2016b).

2.2 Methods

(1) Experimental campaign

A certain number of fundamental properties were first determined before the study of the volume change and viscoelastic behavior of the four concrete mixes: setting time, strength (compressive and tensile) and aggregate properties (Bendimerad et al. 2015; Bendimerad et al. 2016a, 2016b). For consideration of the ageing and the main temperature effects, concrete properties are expressed in function of the equivalent time $t_{eq}$ [Equation (1)], which is based on the Arrhenius law and is function of the age of the material $t$, the evolution of the temperature $T$ (°C), a reference temperature $T_r$ (here 20°C), the universal gas constant $R (=8.314 \text{ J/mol/K})$ and the apparent activation energy $E_a$ (J/mol). The apparent activation energy was determined according to isothermal calorimetry results at 3 temperatures (10 - 20 and 30°C) obtained by Kada-Benameur et al. (2000) and is equal to 35.15 kJ/mol for each composition.

$$t_{eq} (t, T) = \int_0^t \exp \left( \frac{E_a}{R} \left( \frac{1}{273 + T(s)} - \frac{1}{273 + T_r} \right) \right) ds$$ (1)
(2) Assessment of the heat release
Quasi-adiabatic calorimetry (QAB) allows a continuous measurement of the temperature in quasi-adiabatic conditions, which is similar to the evolution of the temperature in case of massive concrete structures. The testing device so-called QAB box was developed at the LCPC laboratory - Laboratoire Central des Ponts et Chaussées (now Ifsttar: Institut français des sciences et technologies des transports, de l’aménagement et des réseaux) for the monitoring of the heat release (Boulay et al. 2010). The QAB calorimeter is composed of a double-walled box filled with an insulating material (Fig. 2). The central part of the device can accommodate a concrete cylinder (dimension: \( \phi 16 \times 32 \text{ cm} \)) accompanied by its mold. A platinum probe is placed in the center of the sample for the monitoring of the temperature of the concrete sample during the whole test. The temperature inside the specimen is both a function of the heat release of the cement paste and the temperature exchanges around the calorimeter. In order to separate the influence of both parameters, a second QAB calorimeter is used and placed in the same room. During the test, the temperature inside the concrete sample is recorded as well as the temperature of the control specimen and the temperature of the room. Tests were performed on \( \pm 15.5 \) kg concrete samples.

(3) Assessment of the free strain
The free strain of the studied concretes is measured from casting using the BTJADE device (Boulay 2012). The test rig is composed of a vertical flexible corrugated PVC mold to monitor the free strain and fixed metallic parts. The whole frame is placed in a temperature controlled bath. A new test protocol, presented in earlier studies (Delsaute et al. 2016b; Delsaute and Staquet 2017), is used for the monitoring of the autogenous strain and the coefficient of thermal expansion. The temperature in the water tank is first imposed to 20°C until the sample temperature is stable. Then, every 160 minutes, thermal variations of \( \pm 3°C \) are applied on a concrete sample. As autogenous and thermal strains occur simultaneously, it is not directly possible to separate both. In order to distinguish strains, it is necessary to have two different temperature histories. For that reason, a fictitious temperature history is created by considering only the values of the total concrete strain \( \varepsilon_{\text{tot}} \) and the concrete temperature \( T \) obtained at the end of the plateau of temperature at 20°C in the water tank. Cubic interpolation is then used to define the total strain and the temperature in case of a curing at 20°C. With these two sets of data, the variation of total strain and temperature is compared for the two different temperature histories to define first the CTE according to Equation (2).

\[
\alpha_p = \frac{\Delta \varepsilon_{\text{tot,1}} - \Delta \varepsilon_{\text{tot,2}}}{\Delta T_1 - \Delta T_2}
\]  

(2)

where the index 1 and 2 are associated to the first and second temperature history respectively. Then the autogenous strain is defined with the removal of the thermal strain from the total strain. Complete details about the device, the test protocol and the data treatment are presented in earlier studies (Boulay 2012; Delsaute and Staquet 2017).

(4) Assessment of the elastic properties
For the monitoring of the elastic properties, cylindrical specimens with a diameter of 97 mm and a height of 550 mm are produced. A dummy specimen with exactly the same dimensions is also produced. Samples are surrounded by 2 self-adhesive aluminum sheets in order to keep the sample in sealed conditions. An electromechanical testing setup with an extensometer in Invar© designed at ULB (Université Libre de Bruxelles) is used for the monitoring of the E-modulus by means of repeated loadings (Fig. 3). The equipment is located in an air-conditioned room with a control system of the temperature and the relative humidity. The longitudinal displacement is measured with an extensometer composed by two rings spaced of 350 mm and three rods on which the 3 displacement sensors placed at 120° are pressed.

![Quasi-adiabatic calorimeter QAB](image)
Three anchorages with elastic blades are used for each ring to assure a good link between the concrete displacement and the sensor.

(5) Assessment of the basic compressive creep
Compressive creep tests were performed on 16 frames designed at ULB (Fig. 4). The load is applied on the sample by increasing flat jack pressure with a pump until 40% of the compressive strength. A cell force is placed on the top of the sample. According to the age at loading and the force applied, the size of the flat jack is adapted. For loading at very early age, flat jacks with very small diameter are used with a transition piece to assure a good stability of the load and a very low eccentricity. Displacements are measured with an extensometer composed by two rings in aluminum spaced of 200 mm and three rods in invar, which support the 3 displacement sensors placed at 120°. A dummy specimen is used for each series of test to monitor the thermal and autogenous strain. Thermocouples are placed inside the dummy mold and in the room in order to monitor the ambient and concrete temperature. The sample is a cylinder with a height of 320 mm and a diameter of 97 mm. Before testing, samples are surrounded by two self-adhesive aluminum sheets. Tests are carried out in a climatic room with a temperature of 20±1°C. Complete details about the test assessment of the basic compressive creep are given by Delsaute et al. (2016a).
3. Experimental results

3.1 Temperature evolution in quasi-adiabatic conditions and heat release

Each minute, the temperature of the sample, the control specimen and the testing room is recorded. Measurement starts around 30 minutes after the first contact between water and cement until a concrete age of minimum 180 hours. In Fig. 5, the recordings of the temperature of the fresh concrete are presented. For each composition, the temperature of the sample increase significantly between an age of 5 and 11 hours. The temperature peak is reached between an age of 23 and 26 hours. The temperature evolution is very similar for each composition. Very low thermal variations were measured in the control specimen (lower than 2.5°C) for each test. From these recordings, the cumulated heat release and the evolution of the temperature in adiabatic condition are defined. The cumulated heat release is computed with consideration of the total heat loss by the calorimeter (Andre and Saintilan 2010), the heat capacity of the concrete components and the difference of temperature between the fresh concrete and the control specimen. The determination of the temperature in adiabatic condition is based on the evolution of the heat release, the activation energy and the heat capacity of the concrete. Complete explanations related to the computation of both parameters are presented by Boulay et al. (2010). For each composition, the evolutions of the cumulated heat release are very close. After an age of 100 hours, a slight difference in the magnitude of the cumulated heat release is observed. At an age of 180 hours, an adiabatic temperature of 57.4, 57.9, 58.7 and 59.6°C is reached for the composition 0RS0RA, 30RS0RA, 0RS30RA and 0RS100RA respectively. As for the cumulated heat release a slight increase of the adiabatic temperature is obtained when using recycled aggregate. The replacement of natural aggregate by recycled one leads to an increase of the heat release and the adiabatic temperature. The total water content is higher for compositions with recycled aggregate and is responsible of a higher cement hydration. Similar observations were already carried out when replacing natural aggregate by lightweight aggregate (Akçay and Tasdemir 2008) or when using super absorbent polymer (Wyrzykowski and Lura 2013).

3.2 Autogenous strain and coefficient of thermal expansion

For each composition, the test has been carried out on two samples coming from the same batch to assure the repeatability of the results. Results presented in Figs. 6 and 7 are the average of both samples. Results of the CTE are given according to the equivalent age in Fig. 6. Two successive stages are observed in the results. During setting, a strong and quasi instantaneous decrease of the CTE takes place during a same very small time window for each composition (between an equivalent age of 6 and 8 hours). During this period, the evolution of the CTE is driven by the amount of water that is not yet chemically bound and by the increase of the stiffness of the cement paste. Then a low decrease or increase of the CTE is observed for each composition until an equivalent age of 24 hours. For some compositions, a minimum is reached and corresponds to the CTE of the solid skeleton (Sellevold and Bjøntegaard 2006). After this

![Fig. 6 Development of the CTE according to the equivalent age.](image)

![Fig. 7 Development of the autogenous strain according to the equivalent age.](image)
period, the CTE does not evolve significantly. For composition with high replacement of natural aggregate by recycled aggregate, the value of the CTE is globally higher. In a hardened state, the CTE of the composition 0RS100RA is 50% higher than the composition 0RS0RA. At very early age, this difference is even more marked. In case of replacement of natural sand by recycled sand, the amplitudes of the CTE for the reference composition and the composition 30RS0RA are very close. This can be attributed to the very low stiffness of the recycled sand in comparison to the recycled gravel. Such observations are explained by the well-known sensitivity of the CTE to the nature of the aggregate (Jib 2013; Siddiqui and Fowler 2014) and the evolution of the relative humidity inside the cement paste (Bjøntegaard and Sellevold 2001; Sellevold and Bjøntegaard 2006).

Autogenous strains are set to zero at the final setting time \( t_{fs} \) and are shown according to the equivalent age in Fig. 7. Three main stages appear in the evolution of the autogenous strain. The first stage starts at the final setting (between 10 and 12 hours according to the composition) and goes on until an equivalent age of 24 hours. During this period, shrinkage is observed and evolves very similarly for each composition with a magnitude varying between 10 and 15 \( \mu \text{m}/\text{m} \) and is associated to the self-desiccation of the cement paste. Then a divergence takes place between the evolutions of the different compositions. For the composition without recycled aggregate, self-desiccation shrinkage continue according to a logarithmic trend. For compositions with recycled aggregate, a swelling starts at an equivalent age of 24 hours. The high porosity and the associated internal curing effect of the recycled gravel or sand are at the origin of these differences of evolution between the compositions. Equivalent observations with lightweight aggregate have been performed previously, for example, by Bentur et al. (2001) and Liu and Hansen (2016). The magnitude of the swelling depends on the amount and type of recycled aggregate. With recycled sand, the amplitude of the swelling is 1 \( \mu \text{m}/\text{m} \) and reached its maximum at an equivalent age of 32 hours. Whereas, with recycled gravel the swelling is higher with a magnitude of 5 and 12 \( \mu \text{m} \) for the composition 0RS30RA and 0RS100RA respectively. Moreover, the swelling takes place on longer duration when using recycled gravel.

### 3.3 Compressive and tensile strength

The compressive strength is measured from an age of 20 hours up to 7 days of age on cube of 10 cm side at a curing temperature of 20°C. Tests to determine compressive strength were performed on a Galdabini 3000kN test machine. The device is controlled in displacement. A same constant displacement rate was imposed to each sample whatever the age at loading during the whole test. Results of the compressive strength \( f_c \) are given according to the equivalent time in Fig. 8. All results correspond to an average of at least two samples. The standard deviation varies between 0 and 0.65 MPa for each composition and age at loading. In addition, results of the compressive strength obtained at an age of 1, 2, 7 and 28 days by Bendimerad (2016) are shown. Concretes with recycled aggregate are characterized by a lower compressive strength development in comparison to the reference concrete without recycled aggregate. The decrease of strength induced by the recycled aggregate is more significant after an equivalent age of 2 days. Such observation was already done by several authors on hardened concrete, for example, by Thomas et al. (2018), Velay-Lizancos et al. (2019, 2016). These results are used to carry out repeated loadings test as explained in the next paragraph. The tensile strength is measured by means of splitting tensile test for ages of 16, 20 and 24 hours at a curing temperature of 20°C. Results of the splitting tensile strength \( f_{st} \) are given according to the equivalent time in Fig. 9. Results correspond to an average of at least two samples. The standard deviation varies between 0.01 and 0.11 MPa for each composition and age at loading. In addition, tensile strength results coming from direct tensile test (ages of 7, 10, 16, 20 and 24 hours) and splitting tensile test (ages of 24, 36, 48, 72, 110, 168 and 300 hours) obtained by Bendimerad et al. (2016) are also shown. During and just after setting, the development of the tensile strength is very similar for each composition. Since an age of 16 hours, concrete composed of recycled sand or gravel are characterized by a lower development of the tensile strength in comparison to the reference concrete without recycled aggregate. This difference increases when the natural gravel are fully replaced by recycled one. These results are used to analyze the cracking sensitivity of the concretes.

### 3.4 Elastic modulus and Poisson’s ratio

Repeated loading tests (Boulay et al. 2014; Delsaute et al. 2016a; Delsaute et al. 2016c; Irfan-ul-Hassan et al. 2016) have started 4 hours after the final setting. Each hour, a load corresponding to 20% of the compressive

![Fig. 8 Evolution of the compressive strength according to the equivalent age.](image-url)
strength is applied in 10 seconds at a constant stress rate then unloaded until a value of 0.014 MPa to always keep contact between the sample and the testing device. These threshold values are chosen to avoid any damage of the sample in compression. The whole test duration is 1 week or even more. The temperature of the room is set to 20°C and the temperature inside the dummy specimen is recorded since the casting. The E-modulus is determined during the repeated loading from the set of recordings (load and displacement in the central section) between 30% and 80% of loading. Results are given according to the equivalent time in Fig. 10.

The substitution of 30% of natural aggregate by recycled one does not change significantly the evolution of the E-modulus while a rate of substitution of 100% induce a decrease of the E-modulus by 5 GPa at an age of 1 week. It is therefore observed that a small replacement of natural gravel by recycled one (here 30%) does not affect significantly the evolution of the E-modulus while a full substitution will decrease strongly the amplitude of the E-modulus since setting. This means that the E-modulus of recycled concrete cannot be calculated based only on the stiffness of the recycled aggregate and the cement paste using a mix law. The substitution of 30% of natural sand by recycled sand induces a decrease of the E-modulus by 4 GPa at an age of 1 week. This corresponds to a reduction of 11% of the E-modulus in comparison to the reference concrete. From results of the literature, similar trends were observed.

On hardened concrete with water-to-cement ratio of 0.4, 0.45 and 0.5 and cement content of 300 - 350 and 450 kg/m³, Thomas, et al. (2018) have shown that the decrease of the E-modulus with the increase in replacement of natural gravel by recycled one is composed of two stages. For replacement level of natural gravel lower than 25%, very small reduction of the E-modulus has been observed (< 5%). While for higher replacement level of natural gravel, a linear and important reduction of the E-modulus was obtained. For concrete mix with a full replacement of natural gravel by recycled one, the E-modulus is reduced by 31 to 39%. On hardening concrete, Velay-Lizancos, et al. (2018) have replaced 0, 8, 20 and 31% of natural sand and gravel by recycled one. Based on the results of the E-modulus since setting, a linear trend is observed between the replacement rate of the natural gravel and sand and the reduction of the E-modulus. For a replacement of 31% of the natural sand and gravel by recycled one, a reduction of 16% was obtained. Such order of magnitude is in agreement with the results obtained in this study when natural sand is replaced by recycled one. The Equation (3) is used to fit experimental data. This equation is composed of one exponential term and was already used for many other compositions to represent the development of the E-modulus since setting (Delsaute 2016).

\[ E(t_{eq}) = E(t_{eq} = \infty) \cdot \exp \left( -\frac{p_E}{t_{eq} - t_p} \right) \]

where \( t_{eq} \) is expressed in hour, \( E_p \) and \( E_r \) are material parameters which are related to the kinetic evolution of the elastic modulus, \( E(t_{eq} = \infty) \) is expressed in GPa and corresponds to the value of the elastic modulus at an infinite time. Values of all parameters are given in Table 3.

In addition, for each repeated loading, the Poisson’s ratio is calculated from the set of recordings (longitudinal and lateral displacement in the central section) on the whole loading. Results are given according to the equivalent time in Fig. 11. For each composition, the Poisson ratio decreases till a minimal value, followed by an increase. Such development of the Poisson’s ratio is in agreement with previous results obtained in the literature (Byfors 1980; Mesbah et al. 2002; Schutter and Taerwe 1996). Concretes with recycled aggregate are characterized by a higher Poisson’s ratio during early age in comparison to the reference concrete without recycled aggregate. At later ages, this difference decreases and a Poisson’s ratio of around 0.2 is obtained for each concrete composition. According to Bernard et al. (Bernard et al. 2003), the decrease of the Poisson’s ratio occurs as long as the water phase is continuous and
is due to the consumption of water during the hydration process. When the cement begins to set, the water phase becomes discontinuous and the evolution of the Poisson’s ratio is then governed by the solid stiffness evolution which will increase the Poisson’s ratio. As aggregates are used in saturated-surface-dry conditions, the total content of water in concrete with recycled aggregate is higher. Moreover recycled aggregate plays the role of water storage agent that refills capillarity pores during the hardening process and avoid or reduce the self-desiccation mechanism with the continuous release of water. The internal curing effect due to the recycled aggregate can explain the higher value of the Poisson’s ratio obtained at early age in concrete with recycled aggregate.

### 3.5 Compressive basic creep

For each composition, 4 compressive creep tests with duration of few weeks were performed. Every test has been carried out on two samples coming from the same batch to assure the repeatability of the results. Results presented below are the average of both samples. The ages at loading of the creep tests were defined on the basis of the evolution of the degree of hydration obtained from quasi-adiabatic calorimetry tests. Compressive creep tests have been started at a same maturity for the different compositions in order to compare the composition for a same hydration of the cement paste and thus the differences in the experimental results will only come from the presence of the recycled aggregate. Degrees of hydration of 0.41, 0.47, 0.58 and 0.69 have been selected which corresponds to an age at loading of around 22, 29, 45 and 92h respectively for each composition.

The compressive creep results are expressed according to the specific creep function $J'$ defined in Equation (4):

$$J'(t, t') = \frac{\varepsilon_{sh}(t, t') - \varepsilon_{sh}(t) - \varepsilon_{cr}(t')}{\sigma} = \frac{\varepsilon_{cr}(t, t')}{\sigma}$$

where $t$ is the age of concrete, $t'$ is the age at loading, $\varepsilon_{sh}$ is the total strain of the loaded specimen, $\varepsilon_{sh}$ is the strain of the dummy specimen, $\varepsilon_{cr}$ is the elastic strain of the loaded specimen, $\varepsilon_{cr}$ is the basic creep strain of the loaded specimen and $\sigma$ is the uniaxial stress applied on the loaded specimen. Results of the specific creep function are presented in Fig. 12 (continuous lines). For each composition, the effect of the age at loading is strongly marked in the evolution of the specific creep especially for the compositions with recycled gravel. Concretes with recycled gravel or sand are characterized by a higher development of the specific creep function in comparison to the reference concrete without recycled aggregate. It is especially true at very early age (age of loading lower than 30 hours), when the magnitude of the specific creep function is around 60% higher for concretes with recycled gravel or sand. At later ages, the specific creep function is between 15 and 20% higher for concretes with recycled gravel. Such increase of the creep function was already observed by many authors on hardened recycled concrete as indicated by Tošić et al. (2019). While the substitution of 30% of natural sand by recycled one increases the specific creep function by 48%. In addition, the rate of replacement of natural gravel by recycled gravel seems to not influence significantly the specific creep function for a substitution range between 30 and 100%.

As proposed by Torrenti and Le Roy (2017), based on the present Model Code 2010 (MC2010), basic creep can be expressed with a logarithmic expression as shown in Equation (5), where the parameter $C$ is related to the global amplitude of the creep, independent of the age at loading, and is expressed in MPa. The parameter $\tau$ is function of the age at loading and the composition, and $\tau$ is expressed in day.

$$J'(t, t') = \frac{1}{C} \ln \left(1 + \frac{t-t'}{\tau} \right)$$

The Equation (5) is used to fit the experimental data by means of least square method for each composition as shown in Fig. 12 (dashed lines). A general very good agreement is obtained between the experimental results and the fitted values whatever the age at loading. It is nevertheless observed that creep function is underestimated during the first hours after loading in each case. Similar observations have already been done for an ordinary concrete, OC (Delsaute et al. 2017). The fitted values of the parameter $\tau$ for each age at loading and of the parameter C are given in Table 4.

As highlighted by Delsaute et al. (2017), the evolution of the parameter $\tau$ is related to the inverse of the
time derivative of the E-modulus. Two kinds of trend were observed. At very early age, the relation between the parameter $\tau$ and the inverse of the time derivative of the elastic modulus follows a power trend at very early age and a linear trend at later age. This is highlighted in Fig. 13, where the parameter $\tau$ is plotted according to the inverse of the derivative of the E-modulus [obtained from Equation (3)]. In comparison, results of an ordinary concrete (Delsaute et al. 2017) are given also in Fig. 13.

The relation between the parameter $\tau$ and the inverse of the time derivative of the E-modulus is given in Equation (6). This relation is used in the section 4 to determine the specific creep function since setting.

$$\tau = \min \left\{ q_1 \left( \frac{dE}{dt} \right)^{-1} + p_1, q_2 \left( \frac{dE}{dt} \right)^{-p_2} \right\}$$

where the concrete parameters $q_1$, $p_1$, $q_2$ and $p_2$ are defined in Table 5.

### 4. Evolution of the stress under restrained conditions

In order to evaluate the influence of recycled gravel and sand on the risk of cracking, a calculation of the restraint of the free deformations is performed according to Equations (7) and (8). The free deformations after setting $\varepsilon_c$ are defined according to the principle of superposition and are the sum of the autogenous deformation $\varepsilon_{au}$ and the thermal deformation $\varepsilon_{th}$ [Equation (7)], drying is not considered in this study.

#### Table 4 Value of parameter $\tau$ from Equation (5).

| $t'$ [h] | $\tau$ [d] | C [GPa] |
|----------|------------|---------|
| 0RS0RA   | 23         | 8.5E-03 | 180     |
|          | 29         | 1.4E-02 |         |
|          | 46         | 3.6E-02 |         |
|          | 93         | 6.0E-02 |         |
| 30RS0RA  | 22         | 9.9E-03 | 123     |
|          | 29         | 3.3E-02 |         |
|          | 45         | 5.5E-02 |         |
|          | 93         | 9.7E-02 |         |
| 0RS30RA  | 20         | 2.1E-03 |         |
|          | 24         | 7.9E-03 |         |
|          | 44         | 8.1E-02 |         |
|          | 92         | 1.6E-01 |         |
| 0RS100RA | 24         | 5.2E-03 |         |
|          | 29         | 3.0E-02 |         |
|          | 47         | 1.5E-01 |         |
|          | 92         | 2.1E-01 |         |

The relation between the parameter $\tau$ and the inverse of the time derivative of the E-modulus is given in Equation (6). This relation is used in the section 4 to determine the specific creep function since setting.

$$\tau = \min \left\{ q_1 \left( \frac{dE}{dt} \right)^{-1} + p_1, q_2 \left( \frac{dE}{dt} \right)^{-p_2} \right\}$$

where the concrete parameters $q_1$, $p_1$, $q_2$ and $p_2$ are defined in Table 5.

Fig. 12 Basic compressive creep - the continuous lines correspond to experimental results and dashed-lines correspond to the model.
For the determination of the stress under restrained condition, the development of the elastic and relaxation properties are important parameters. In order to avoid cracking, the Equation (8) must be verified.

\[ f_\epsilon < \sum_{i=1}^{n} \Delta\epsilon_i \cdot E(t_i) \cdot \varphi_i (t_{eq}, t) < f_\epsilon \]

(8)

The amplitude of the thermal variations inside concrete element is function of the binder properties, the massivity of the concrete structure and the environment around. Highest thermal variation occurs in case of massive structure. Such thermal variation corresponds to the evolution of the temperature recorded in the concrete sample placed in the QAB calorimeter and can be considered as an upper bound. For thin concrete element, the magnitude of the thermal variation is lower. Harden- ing concrete structures are generally subjected to internal and external restraint. The restraint condition of a given section in a concrete structure depends on its location and the general configuration of the structure. The degree of restraint of the free deformation will vary also according to the stiffness of the concrete. In the frame of this study, the worst situation is considered: the full restraint of the free deformation. This is for example the case for a thin wall casted in a stiff foundation. For these both reasons, two scenarios were investigated. Firstly, only the full restrained situation of the autogenous strain is considered. Secondly, both autogenous and thermal strains are fully restrained.

4.1 Restrained of the autogenous strain

In the first scenario, the autogenous strains are fully restrained. First, the elastic stresses are computed based on the development of the autogenous strain and the E-modulus only (Fig. 14, continuous lines). The stress starts to build up at the final setting time. Until an equivalent age of 24 hours, tensile stresses develop for each composition. A similar magnitude of around 0.16 MPa is obtained except for the 30RS0RA composition (0.08 MPa). Then a divergence takes place between the evolutions of the different compositions. For the composition without recycled gravel, the tensile stress continues to increase while with recycled gravel a decrease of the tensile stress is obtained. Between an equivalent age of 24 and 40 hours, no significant stress variation is observed when natural sand is replaced by recycled one. For the composition 0RS100RA, stresses switch to compression at an equivalent age of 56 hours. At an equivalent age of 260 hours, the elastic stresses computed for the composition without recycled aggregate are equal to 0.7 MPa while compressive stresses of -0.1 MPa were computed for the composition 0RS100RA. For the compositions 30RS0RA and 0RS30RA, the elastic stresses are 0.28 and 0.07 MPa at an equivalent age of 260 hours. Thus, in this scenario, the decrease of the E-modulus and the autogenous shrinkage induced by the presence of recycled gravel/sand leads to a significant decrease of the elastic stress. This is especially true with recycled gravels. For the consideration of the viscous behavior of concrete materials, the relaxation coefficient was deduced analytically from the experimental results of the specific creep as indicated in Equations (9) and (10) (Van Breugel 1980).

\[ \varphi_i (t, t') = \frac{\epsilon_i (t, t')}{\epsilon_i (t')} = J (t, t') \cdot E(t') \]

(9)
where $\varphi(t,t')$ is the creep coefficient. The impact of viscous properties at very early age, in case of full restrained of the autogenous deformation, is highlighted on the development of the stress as shown in Fig. 14 (dashed lines). First, creep and relaxation have the positive effect to reduce the development of the tensile stress. Then the influence of the creep and relaxation is different for each composition according to the development of the elastic stress and the aging of the relaxation coefficient. At an equivalent age of 260 hours, the viscoelastic stress computed for the composition without recycled aggregate are equal to 0.41 MPa while stresses of 0.17, 0.03 and -0.07 MPa were computed for the composition 30RS0RA, 0RS30RA and 0RS100RA respectively. Thus, after an equivalent age of 260 hours, stresses are reduced by 42% for the composition without recycled aggregate and the composition with recycled sand. A reduction of 39 and 42% is obtained for the composition 0RS30RA and 0RS100RA respectively.

4.2 Restrained of the autogenous and thermal strain

The thermal strains were computed by considering the experimental results of the CTE and the evolution of the temperature recorded in the QAB. As in the first scenario, the substitution of natural gravel/sand by recycled gravel/sand leads to a global decrease of the stress induced by the restraint of the autogenous and thermal strain (Fig. 15). During the first 48 hours after mixing (in equivalent time), compressive stresses are observed for each compositions and are mainly generated by the restraint of the thermal deformations. Since the temperature variations are very similar for all compositions, the differences in stresses observed between each composition come mainly from the differences in the evolution of the elastic modulus and the CTE. At around an equivalent age of 50 hours the peak of compressive elastic stresses is reached. The elastic stresses calculated for the composition without recycled aggregate are equal to -0.49 MPa whereas elastic stresses of -0.71, -1.00 and -1.15 MPa were calculated for the 30SR0GR compositions, 0SR30GR and 0SR100GR respectively. Then, due to the temperature decrease, stresses evolve in the opposite direction and switch to tension. At an equivalent age of 260 hours, the elastic stresses calculated for the composition without recycled aggregate are equal to 3.82 MPa whereas stresses of 3.37, 2.91 and 2.80 MPa were calculated for the compositions 30SR0GR, 0SR30GR and 0SR100GR respectively. These different evolutions are explained by the lower modulus of elasticity and the lower increase of the CTE of the compositions with recycled aggregates. When considering the creep/relaxation properties according to Equations (9) and (10), a general decrease of the stress is observed. The peak of compressive stresses is reduced by 30, 33, 38 and 38% and stresses switch to tension at an equivalent age of 38, 82, 90 and 101 hours for the composition 0RS0RA, 30RS0RA, 0RS30RA and 0RS100RA respectively. At an equivalent age of 260 hours, the viscoelastic stress computed for the composition without recycled aggregate are equal to 2.3 MPa while stresses of 1.9 MPa were computed for the composition 30RS0RA, 0RS30RA and 0RS100RA. Thus, after an equivalent age of 260 hours, tensile stresses are reduced by 41% for the composition without recycled aggregate and the composition with recycled sand. A reduction of 34 and 31% is obtained for the composition 0RS30RA and 0RS100RA respectively. Thus, it is observed that the replacement of natural aggregate by recycled one increases the compressive stresses, delays the switch to tension and decrease the amplitude of the tensile stresses. Finally, the stresses are compared to the tensile strength. For each composition, the calculated stress exceeds the tensile strength. However, the age of cracking is different. For the composition without recycled aggregate, a cracking age of 168 hours was calculated while crack ages of 190, 180 and 175 hours were calculated for compositions 30SR0GR, 0SR30GR and 0SR100GR respectively. It is therefore observed that the substitution of natural aggregates by recycled aggregates delays the age of cracking of the materials and more generally reduces the risk of cracking of concrete element under restrained conditions.

In addition, several physical mechanisms were not considered in the calculation and are expected to affect the stress development. The following phenomena were not considered:

a. The thermal variation influences the development of the autogenous strain. As explained by Jensen and Hansen (Jensen and Hansen 2001), thermal variation changes the internal relative humidity of cement based materials and consequently modifies the development of the self-desiccation shrinkage (Carette and Staquet 2018).

![Stress development in case of full restrained of the autogenous and thermal deformations](image-url)
b. In case of microcracking development, the internal curing effect of the recycled aggregate can lead to a self-healing of the microcracks. Moreover, it is nevertheless questionable whether the internal curing effect of recycled aggregate is attenuated when the concrete is under compressive load (Carette et al. 2018).

c. The behavior under tension and compression is different for cement based materials. In particular, the viscoelastic behavior has been defined on the basis of repeated compressive loadings test and compressive creep tests. According to the literature, the elastic modulus seems to be slightly higher in tension than in compression. This difference varied between 9 and 15% generally (Atrushi 2003; Bissonnette et al. 2007; Hagihara et al. 2000; Yanni 2009; Yoshitake et al. 2012) and can be related to the difference of stress level and the influence of microcracking process (Delsaute 2016; Delsaute et al. 2016). Moreover, the tensile short term creep is much lower than the compressive short term creep (Delsaute 2016c). The consideration of the tensile viscoelastic behavior leads then to an increase of the tensile stresses.

d. In case of unloading, creep recovery should be considered.

e. The thermal variation influences the development of the basic creep properties and consequently the stress relaxation (Hauggaard et al. 1999).

f. For stress level higher than 50%, the viscoelastic properties are non-linear (Switek et al. 2016) and a coupling exists between creep and damage (Rossi et al. 2012). Moreover, it is nevertheless questionable whether the viscoelastic properties are linear for stress level lower than 50%. Recent studies question this fact (Delsaute 2016; Delsaute et al. 2016c; Forth 2014).

Therefore, further investigations are still needed to understand how recycled aggregate acts in the risk of cracking of concrete element under restrained conditions.

5. Conclusions

A new experimental methodology based on repeated testing method is presented for the characterization of the early age behaviour of concrete composed of recycled sand and gravel in sealed conditions. The substitution of natural aggregate by recycled one is studied on four concretes for which recycled gravels corresponds to 0 - 30 and 100% of the gravels volume fraction and recycled sand corresponds to 0 - 30% of the sand volume fraction. The presence of recycled gravel and sand induces:

1. a decrease of the autogenous shrinkage induced by the internal curing effect of the recycled aggregate,
2. an increase of the coefficient of thermal expansion since setting induced by the higher CTE of recycled aggregate and their internal curing effect,
3. a global reduction of the compressive strength and the elastic modulus,
4. an increase of the Poisson’s ratio only at early age,
5. an increase of the basic creep which is function of the maturity of the concrete. At very early age, an increase of 60% is observed with recycled sand and gravel whereas, at later ages, an increase between 15 and 20% is obtained with recycled gravel and 48 % with recycled sand.

Based on these results, an elastic and viscoelastic calculation of the full restraint of the autogenous and thermal deformations was performed. It is shown that the use of recycled gravel and sand decreases the risk of cracking of concrete structure. This study highlights the interest of the use of recycled aggregate for mass concrete.

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References

Akcay, B. and Tasdemir, M. A., (2008). “Internal curing of mortars by lightweight aggregates and its effects on hydration.” *Can. J. Civ. Eng.*, 35(11), 1276-1284.

Andre, J. and Saintilan, R., (2010). “Calibration of a QAB calorimeter.” *Bulletin des Laboratoires des Ponts et Chaussées*, 278, 43-47.

Atrushi, D. S., (2003). “Tensile and compressive creep of early age concrete: testing and modelling.” Thesis (PhD). The Norwegian University of Sciences and Technology, Trondheim, Norway.

Behera, M., Bhattacharyya, S. K., Minocha, A. K., Deoliya, R., and Maiti, S., (2014). “Recycled aggregate from C&D waste & its use in concrete - a breakthrough towards sustainability in construction sector: a review.” *Constr. Build. Mater.*, 68, 501-516.

Bendimerad, A. Z., Roziere, E. and Loukili, A., (2015). “Combined experimental methods to assess absorption rate of natural and recycled aggregates.” *Mater. Struct.*, 48(11), 3557-3569.

Bendimerad, A. Z., (2016). “Comportements au jeune âge et différe des bétons recyclés: influence de la saturation initiale en eau et du taux de substitution.” Thesis (PhD). Ecole Centrale de Nantes, Nantes, France.

Bendimerad, A. Z., Delsaute, B., Roziere, E., Staquet, S. and Loukili, A., (2016a). “Effect of recycled aggregate concrete on early age behaviour.” In: M. Azenha, I. Gabrieli, D. Schlicke, T. Kanstad and O. M. Jensen, Eds. *Proc. International RILEM Conference on Materials, Systems and Structures in Civil Engineering: Service Life of Cement-Based Materials*...
Delsaute, B., Boulay, C. and Staquet, S., (2016a). “Plastic shrinkage and cracking risk of recycled aggregates concrete.” Constr. Build. Mater., 121, 733-745.

Bendimerad, A. Z., Rozière, E. and Loukili, A., (2016b). “Prevention of autogenous shrinkage in high-strength concrete by internal curing using wet lightweight aggregates.” Cem. Conc. Res., 31(11), 1587-1591.

Bentur, A., Igarashi, S. I. and Kovler, K., (2001). “Interaction between thermal dilation and autogenous deformation in high performance concrete.” Mater. Struct., 34(239), 266-272.

Boulay, C., Staquet, S., Delsaute, B., Carette, J., Azenha, M., Dumoulin, C., Karaikos, G., Deraemaeker, A. and Staquet, S., (2016c). “Testing concrete E-modulus at very early ages through several techniques: an inter-laboratory comparison.” Strain, 52(2), 91-109.

Boulay, C., Boulay, C., Granja, J., Carette, J., Azenha, M., Bendimerad, A. Z., Rozière, E. and Loukili, A., (2016b). “Quasi-adiabatic calorimetry for concretes: influential factors.” Bulletin Des Laboratoires Des Ponts et Chaussees, 19-36.

Byfors, J., (1980). “Plain concrete at early ages.” Thesis (PhD). Swedish Cement and Concrete Res. Inst.

Carette, J. and Staquet, S., (2018). “Unified modelling of the temperature effect on the autogenous deformations of cement-based materials.” Cem Concr. Compos., 94, 62-71.

Carette, J., Delsaute, B. and Staquet, S., (2018). “Estimating the stress development in early age concrete with mineral additions from coupled measurements.” In: M. Azenha, D. Schlicke, F. Benboudjema and A. Jędrzejewska Eds. Proc. SynerCrete’18 International Conference on Interdisciplinary Approaches for Cement-based Materials and Structural Concrete, Funchal, Portugal 24-26 October 2018. 231-236.

Delsaute, B., Torrenti, J. M. and Staquet, S., (2016b). “Monitoring and modeling of the early age properties of the Vercors concrete.” In: TINCE 2016, The 3rd Technological Innovations in Nuclear Civil Engineering, Paris, France 5-9 September 2016, 12.

Delsaute, B., Boulay, C., Granja, J., Carette, J., Azenha, M., Dumoulin, C., Karaikos, G., Deraemaeker, A. and Staquet, S., (2016c). “Testing concrete E-modulus at very early ages through several techniques: an inter-laboratory comparison.” Strain, 52(2), 91-109.

Delsaute, B. and Staquet, S., (2017). “Decoupling thermal and autogenous strain of concretes with different water/cement ratios during the hardening process.” Advances in Civil Engineering Materials, 6(2), 22.

Delsaute, B., Torrenti, J. M. and Staquet, S., (2017). “Modeling basic creep of concrete since setting time.” Cem. Concr. Compos., 83, 239-250.

Delsaute, B. and Staquet, S., (2018). “Influence of recycled aggregate and recycled sand on the development of the earlage properties of concrete since setting.” In: M. Azenha, D. Schlicke, F. Benboudjema and A. Jędrzejewska Eds. Proc. SynerCrete’18 International Conference on Interdisciplinary Approaches for Cement-based Materials and Structural Concrete, Funchal, Portugal 24-26 October 2018. 231-236.

De Schutter, G. D. and Taerwe, L., (1996). “Degree of hydration-based description of mechanical properties of early age concrete.” Mater. Struct., 29(6), 335-344.

DOT, (1993). “A study of the use of recycled paving material.” Washington DS, USA: US Department of Transportation, Federal Highway Administration and Environmental Protection Agency.

Dhir, R. K., de Brito, J., Silva, R. V. and Lye, C. Q., (2019a). “Availability of recycled aggregates in sustainable construction materials.” In: R. K. Dhir, J. de Brito, C. J. Lynn, R. Silva and C. Q. Lye Eds. Sustainable Construction Materials. Amsterdam: Elsevier, 35-56.

Dhir, R. K., de Brito, J., Silva, R. V. and Lye, C. Q., (2019b). “Potential for the recycled aggregate market.” In: R. K. Dhir, J. de Brito, C. J. Lynn, R. Silva and C. Q. Lye Eds. Sustainable Construction Materials. Amsterdam: Elsevier, 585-601.

Dhir, R. K., de Brito, J., Silva, R. V. and Lye, C. Q., (2019c). “Processing of recycled aggregates in sustainable construction materials.” In: R. K. Dhir, J. de Brito, C. J. Lynn, R. Silva and C. Q. Lye Eds. Sustainable Construction Materials. Amsterdam: Elsevier, 57-88.

Dosho, Y., (2007). “Development of a Sustainable Concrete Waste Recycling System.” J. Adv. Concr. Technol., 5(1), 27-42.

fib, (2013). “Code-type models for structural behaviour of concrete: background of the constitutive relations and material models in the fib model code for
concrete structures 2010 (fib bulletin no. 70).”
Lausanne, Switzerland: Federation Internationale du Beton.
Forth, J. P., (2014). “Predicting the tensile creep of concrete.” Cem Concr. Compos., 55, 70-80.
Hagiwara, S., Nakamura, S., Masuda, Y. and Kono, M., (2000). “Experimental study on mechanical properties and creep behavior of high-strength concrete in early age.” Concr. Res. Technol., 11(1), 39-50.
Hauggaard, A., Damkilde, L. and Hansen, F., (1999). “Transitional thermal creep of early age concrete.” Engineering, 125, 458-465.
Irex, (2018). The French National Project “Recybeton” for research and development.
Irfan-ul-Hassan, M., Pichler, B., Reihsner, R. and Hellmich, C., (2016). “Elastic and creep properties of young cement paste, as determined from hourly repeated minute-long quasi-static tests.” Cem. Concr. Res., 82, 36-49.
Jensen, O. M. and Hansen, P. F., (2001). “Autogenous deformation and RH-change in perspective.” Cem. Concr. Res., 31(12), 1859-1865.
Kada-Benameur, H., Wirquin, E. and Duthoit, B., (2018). “Crushing characteristics of a recycled aggregate.” In: Proc. International Conference on Sustainable Building, Oslo, Norway.
Karlsen, J., Petkovic, G. and Lahus, O., (2002). “A Norwegian certification scheme for recycled aggregate (RCA).” In: Proc. International Conference on Sustainable Building, Oslo, Norway.
Kuosa, H., (2012). “Reuse of recycled aggregates and other C&D wastes.” Research Report VTT-R-05984-12 of the VTT Research Technical Center, Finland, 72.
Levy, S. M. and Helene, P., (2004). “Durability of recycled aggregates concrete: a safe way to sustainable development.” Cem. Concr. Res., 30(2), 301-305.
Liu, Z. and Hansen, W., (2016). “Aggregate and slag cement effects on autogenous shrinkage in cementitious materials.” Constr. Build. Mater., 121, 429-436.
Mani, S., (2014). “Studies on fresh and hardened properties of recycled aggregate concrete with quarry dust.” ACI Mater. J., 111(3).
Marinković, S., Radonjanin, V., Malešev, M. and Ignjatović, I., (2010). “Comparative environmental assessment of natural and recycled aggregate concrete.” Waste Manage., 30(11), 2255-2264.
Mesbah, H. A., Lachemi, M. and Aitcin, P. C., (2002). “Determination of elastic properties of high-performance concrete at early ages.” ACI Mater. J., 99(1), 37-41.
Park, S. S., Kim, S. J., Chen, K., Lee, Y. J. and Lee, S. B., (2018). “Crushing characteristics of a recycled aggregate from waste concrete.” Constr. Build. Mater., 160, 100-105.
Pedro, D., de Brito, J. and Evangelista, L., (2014). “Influence of the crushing process of recycled aggregates on concrete properties.” Key Eng. Mater., 634, 151-162.
Rossi, P., Tailhan, J. L., Le Maou, F., Gailliet, L. and Martin, E., (2012). “Basic creep behavior of concretes investigation of the physical mechanisms by using acoustic emission.” Cem. Concr. Res., 42(1), 61-73.
Sellevold, E. J. and Bjontegaard, Ø., (2006). “Coefficient of thermal expansion of cement paste and concrete: Mechanisms of moisture interaction.” Mater. and Struct., 39, 809-815.
Siddiqui, M. S. and Fowler, D. W., (2014). “Optimizing coefficient of thermal expansion of concrete and its importance on concrete structures.” Constr. Mater. Struct., 47-56.
Switek, A. E., Denarié, E. and Brühwiler, E., (2016). “Early age creep and relaxation of UHPFRC under low to high tensile stresses.” Cem. Concr. Res., 83, 57-69.
Tam, V. W. Y., Soomro, M. and Evangelista, A. C. J., (2018). “A review of recycled aggregate in concrete applications (2000-2017).” Constr. Build. Mater., 172, 272-292.
Thomas, J., Thaickavil, N. N. and Wilson, P. M., (2018). “Strength and durability of concrete containing recycled concrete aggregates.” J. Build. Eng., 19, 349-365.
Torreni, J. M. and Le Roy, R., (2017). “Analysis of some basic creep tests on concrete and their implications for modeling.” Struct. Concr., 19(2), 483-488.
Tosić, N., de la Fuente, A. and Marinković, S., (2019). “Creep of recycled aggregate concrete: experimental database and creep prediction model according to the fib model code 2010.” Constr. Build. Mater., 195, 590-599.
Van Breugel, K., (1980). “Relaxation of young concrete.” Thesis (PhD). TU Delft, Delft, Netherlands.
Velay-Lizancos, M., Martinez-Lage, I. and Vazquez-Burgo, P., (2019). “The effect of recycled aggregates on the accuracy of the maturity method on vibrated and self-compacting concretes.” Archiv. Civ. Mech. Eng., 19(2), 311-321.
Velay-Lizancos, M., Martinez-Lage, I., Azenha, M. and Vázquez-Burgo, P., (2016). “Influence of temperature in the evolution of compressive strength and in its correlations with UPV in eco-concretes with recycled materials.” Constr. Build. Mater., 124, 276-286.
Velay-Lizancos, M., Martinez-Lage, I., Azenha, M., Granja, J. and Vazquez-Burgo, P., (2018). “Concrete with fine and coarse recycled aggregates: E-modulus evolution, compressive strength and non-destructive testing at early ages.” Constr. Build. Mater., 193, 323-33.
Wyzykowski, M. and Lura, P., (2013). “Controlling the coefficient of thermal expansion of cementitious materials – a new application for superabsorbent
polymers.” Cem. Concr. Compos., 35(1), 49-58.
Yanni, V. Y. G., (2009). “Multi-scale Investigation of Tensile Creep of Ultra High Performance Concrete for Bridge Applications.” Thesis (PhD). Georgia Institute of Technology.
Yehia, S., Helal, K., Abusharkh, A., Zaher, A. and Istaitiyeh, H., (2015). “Strength and durability evaluation of recycled aggregate concrete.” Int. J. Concr. Struct. Mater., 9(2), 219-239.

Yoshitake, I., Rajabipour, F., Mimura, Y. and Scanlon, A., (2012). “A prediction method of tensile Young’s modulus of concrete at early age.” Adv. Civ. Eng., 2012, 1-10.
Zhao, Z., Remond, S., Damidot, D. and Xu, W., (2015). “Influence of fine recycled concrete aggregates on the properties of mortars.” Constr. Build. Mater., 81, 179-186.