CREEP BEHAVIOUR OF ALKALI-SILICA REACTION DAMAGED CONCRETE WITH SLOW-REACTING AGGREGATES

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ABSTRACT

Concrete structures damaged by alkali-silica reaction (ASR) remain in use in several cases for a long period of time. To calculate the residual strength and the deformation of ASR damaged structures knowledge of the strength, elastic modulus and creep are required.

Concretes with four types of slow-reacting aggregates have been exposed in German fog chamber at 40°C for 560 days. The aggregates present different characteristics and differ in ASR susceptibility. Four aggregates were selected for his research, a greywacke, two quartz porphyries and a crushed gravel from the Upper Rhine valley. Compressive strength, static modulus of elasticity as well as creep and shrinkage deformations were measured at fixed intervals. It is shown that static modulus of elasticity is significantly more affected by ASR than compressive strength. Furthermore, ASR affects the creep behaviour, which depends strongly of the kinetic rate (evolution) of the chemical reaction.

Keywords: alkali-silica reaction, creep, shrinkage, mechanical properties

1 INTRODUCTION

It is well-known that ASR generates a significant reduction in mechanical properties such as tensile strength and modulus of elasticity of concrete. These properties are much more affected than compressive strength [1, 2, 3]. In a study performed by [4], it was found that the elastic deformations of AAR damaged concrete were three and half times larger than those of sound concrete, whereas the creep strain was two and a half to four times larger. Several experimental studies have been published in which concrete affected by ASR was subjected to uni-axial stress [5, 6, 7, 8]. An overview of the works is found in [9]. A common feature of those studies is that ASR expansion is suppressed in the direction of the load by the presence of high stresses. Dunant [8] found, among other things, that applied stress affects the kinetics of ASR expansion due to accelerated damage evolution under load. In this case splitting of the aggregates occurred earlier when load was applied. For his experimental study, he used slow-reacting aggregates. Giorla [10] extend the microstructural model of Dunant [8] to account for creep of the cement paste and its coupling with ASR damage. The model uses an explicit representation of the microstructure to characterize the location of the degradation as well as the role of viscous stress relaxation in the paste.

In order to study the relationship between the progress of ASR and the evolution of the mechanical properties of concrete a new approach was applied. To prevent, that applied stress affects the kinetics of expansion due to accelerated damage evolution under load causing the splitting of the aggregates, creep, modulus of elasticity and compressive strength were measured at fixed intervals from pre-stored concretes. The concretes in this study were made with slow-reacting aggregates with different mineralogy which differ in ASR sensitivity.

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2 MATERIALS AND METHODS

2.1 General

The experimental program includes the examination of 4 different concretes, with different ASR sensitivity, which are tested under the same exposure conditions. Measurements of creep and shrinkage-deformations as well static modulus of elasticity and compressive strength were carried out at selected periods.

2.2 Aggregates used

Four crushed aggregates were chosen for this research. A greywacke from the lower Harz (GW), a quartz porphyry from the Halle Porphyry Complex (QP), a quartz porphyry from the Black Forest (QP(SW)) and a crushed gravel (boulders) from the Upper Rhine valley (OR). The composition of the aggregates has been described elsewhere [3, 11]. ASR sensitivity of the aggregates was assessed with the accelerated mortar bar test according to [12] which is derived from [13] and [14]. Additionally, ASR sensitivity of the aggregates was assessed within a period of 560 days with the fog chamber test at 40 °C used in Germany, similar to the widespread internationally concrete prism test (RILEM AAR-3). With the mentioned tests, the greywacke (GW), quartz porphyry (QP) and crushed gravel from the Upper Rhine valley (OR) were found to be reactive while the quartz porphyry (QP(SW)) was considered non-reactive.

2.3 Concrete composition

The composition of the four concrete mixes is as follows: Portland cement CEM I 32.5 R [15] with 1.30% by mass Na_2O equivalent, cement content of 400 kg/m^3, water-cement ratio of 0.45, and grading curve almost following Fuller curve, with a maximum grain size of 16 mm according to DIN 1045-2 [16]. 30% by vol. of the aggregates consist of non-reactive sand up to 2 mm grain size while 40% with grain size 2-8 mm and 30% of grain size 8-16 mm, both selected from the aggregates described in 2.2.

2.4 Specimens and exposure conditions

From 9 cylinders of each concrete tested, two were used for the determination of ASR expansion, two were used for shrinkage measurements, two were loaded, and three cylinders were selected for the determination of the instantaneous deformations (static modulus of elasticity). Cylinders with 300 mm height and 150 mm diameter were used (surface/volume ratio = 0.33). For the determination of the compressive strength, three cubes with 150 mm edge length (surface/volume ratio = 0.40) for each concrete mixture were used.

After mixing the concrete mixtures, the specimens were stored at 20°C and 95% RH for 28 days. After this first storage, the concrete specimens were placed in a fog chamber at (40 ± 2.0)°C over 560 days. Measurements of the expansion were taken continuously up to 560 days. Compressive strength and the static modulus of elasticity were determined at 28, 140, 280, and 560 days.

Creep and shrinkage were performed on specimens that were stored at 20°C and 95% RH as well as 140 days, 280 days and 560 days in a fog chamber at (40 ± 2.0)°C. Creep tests were carried out with a load corresponding to one third of the characteristic 28 days cylinder strength (= 0.85 ($f_{c,cube}$ – 8)), which were stored at 23°C and 80% RH.

The specimens remained under load over 365 days. Deformation was measured in the load direction (longitudinally) on three different positions by using a dial gauge (see Fig. 1). The measuring distance in the direction of load was 150 mm, measured to an accuracy of 1/1000 mm. The measuring distance across the direction of load was not measured. Shrinkage deformation was measured in longitudinal direction without load over 365 days (see Fig. 1).

The test rigs for long-time creep were developed and produced at the Materials Testing Institute University of Stuttgart. The application of the load is carried out with a hydraulic jack operated with a hydraulic hand pump. After application of the load, the force is maintained by Belleville springs. The control of the applied load is measured by means of load cells. A picture of the creep rig and a detailed drawing is illustrated in Figure 1.

3 RESULTS

Expansion

The mean expansion of two cylinders is plotted in Figure 2 as a function of time. Figure 2 shows the measurements on concrete cast with OR, GW, QP and QP(SW). The determination of the expansion carried out on the cylinders shows the typical time-evolution of ASR-induced strains: Latency times of about 28 (OR), 140 (GW) and 308 days (QP), characteristic times of about 252 (OR), 196 (GW) and 168 days (QP), as well as asymptotic strains of about 4.79 (OR), 2.62 (GW) and 1.05 mm/m (QP) (Fig. 2). The expansion of the non-reactive concrete with QP(SW) is very low and reaches 0.36 mm/m after 365 days.

Compressive strength

The compressive strength was determined on 150 mm cubes. All values are the mean of three specimens. Table 1 summarizes the values of compressive strength after 28 days and after exposure in fog chamber. Table 1 shows that after 28 days, the compressive strength for all tested concretes were similar. Because of the proper curing conditions in the fog chamber (high temperature and high humidity) the compressive strength increased with time for all concretes mixtures. The highest value of compressive strength after 560 days was achieved by the concrete with QP(SW) reactive aggregate. The lowest value of compressive strength after 560 days was achieved by the concrete with OR reactive aggregate.

Modulus of elasticity

The static modulus of elasticity was measured by compression of cylinders. The absolute values of the static modules of elasticity are presented in Table 2. In addition values of the static modulus of elasticity (values in bracket) were normalized with respect to the reference value after 28 days. The values of 28 days storage in moisture cabinet differ because of the mineralogical character of the aggregates. If no ASR occurred (QP(SW)), the static modulus of elasticity would have increased with exposition time in fog chamber. However, as ASR expansion and development increases, the static modulus of elasticity drops substantially. If somehow ASR stops its further development, the static modulus of elasticity start increasing again.

Creep

Figures 3, 4, 5 and 6 show the development of creep. Creep was denoted by ε_{cc}, meaning the entire measured deformation ε_c of the loaded specimen, disregarding the instantaneous deformation ε_{el} while the load is applied and shrinkage deformations ε_s measured on the unloaded specimen. The creep deformation of a loaded specimen is given by as follows:

$$\varepsilon_{cc}(t) = \varepsilon_c(t) - \varepsilon_{el}(t_0) - \varepsilon_s(t) \quad (1)$$

where t = age of concrete, and t_0 = age at load application.

The results of concrete incorporating OR are summarized in Figure 3, where the development of specific creep with time, for loading ages of 28, 140, 280 and 560 days, is compared. The figure shows that creep magnitude for the loading age of 140 days is the highest (this period is considered a period of reaction in progress - see Figure 2). When the threshold of the reaction is attained after 280 and 560 days, creep magnitude decreases. Figure 4 shows the results of specific creep of concrete with GW reactive aggregate. As mentioned before, the reaction occurs later and slower compared with concrete incorporating OR aggregate. After 280 days the reaction is still in progress. For this loading period, the creep magnitude is the highest. After 560 days, when the threshold of the reaction is achieved, creep magnitude decreases. Figure 5 shows the results of concrete incorporating QP. After 280 days no reaction occurs. Thus the creep magnitude is lower than after 140 days because of good curing conditions. Compared with 140 and 280 days, the threshold of the reaction after 560 days is achieved. Thus the creep magnitude is higher. Figures 3,4 and 5 reveal a higher creep response when the reaction is in progress and a stiffer response when the reaction has achieved their threshold. The results of concrete with QP(SW) are summarized in Figure 6, where the development of specific creep with time, for loading ages of 28, 140, 280 and 560 days, is compared. The figure reveals a higher creep response for 28-day concrete and a stiffer response for older concrete.

4 DISCUSSION

Influence of alkali leaching

The observed threshold of the expansion measurements of concretes with reactive aggregates (OR, GW, QP) is probably due to the lack in alkalis likely caused by leaching or chemical consumption. The problem of alkali leaching on expansion measurements from specimens under humid conditions is a well-known issue [17]. According to [18], under extremely humid conditions, like in the German fog chamber with temperature of 40°C, intensive alkali leaching occurs. For the fog chamber test concrete prisms (100 x 100 x 500 mm³) are used normally. One effective measure to reduce the amount of alkali leaching during the test is to increase the cross-section of samples. The rate and amount of alkali leaching decreases when the cross-section is increased since the alkalis have to diffuse a longer distance. The advantage of increasing the sample size is reported by Bakker [19], Thomas [20] and Lindgard [21]. In this work, cylinders with 150 mm x 300 mm were used for expansion measurement as well as determination of modulus of elasticity, creep and shrinkage. The surface/volume ratio of cylinders (0.33) is less than from concrete prisms (0.44) or from the ASTM prisms (0.64).

In the literature, nothing could be found about the influence of leaching on the mechanical properties of ASR affected concrete. However one can assumed, leaching very likely changes ASR final expansion and could even influence expansion rate, which finishes by changing the attained over a fixed period of time [19] and thus the mechanical properties of affected materials at this specific time.

General

Considering the microscopic observations of Ben Haha [22], Dunant [8] Mielich [23] and Sanchez et al. [24], it has been found that ASR generates very few damage in the cement paste (microcracking), at least for low and moderate expansion levels. Therefore, one could assume that any loss of mechanical properties is mostly driven by the damage in the aggregate particles.

Compressive strength

The compressive strength of ASR affected concrete is influenced by the cement paste and depends on water-cement ratio and porosity. For all concrete mixtures cement content and water-cement ratio have been kept constant. Although the compressive strength increased with time for all mixtures, (Table 1), the compressive strength of concrete cast with OR aggregate showed a small increase (11% after 140 days) as well as the concrete cast with QP(SW) (33% after 140 days). Only damage in the cement paste causes the difference in the compressive strength and not the damage in the aggregate particles.

Elastic modulus of concrete and aggregate

Compared to the compressive strength, the elastic modulus of concrete is influenced by cement paste and aggregates. This means that the elastic modulus of concrete is determined by modulus of elasticity of cement paste and modulus of elasticity of aggregate.

Copuroglu [25] studied three types of rock in warm alkaline solution and found a reduction of the elastic modulus which was supposedly due to silica dissolution. Ben Haha [22] found that alkaline solution leads to a reduction of fracture energy and the brittleness of reactive rocks. Reinhardt and Mielich [26] showed that the modulus of elasticity of ASR-sensitive aggregates decreased with the time of exposure in alkaline environment. According to [26] is this degradation feature due to the solubility and mobilization of rock minerals which depends strongly on a high concentration of OH^-. All mentioned alkali-sensitive aggregates are unstable in high alkaline environment and undergo an alteration. This deterioration feature of alkali-sensitive aggregates is irreversible and affects mechanical properties of concrete which depend on elastic modulus of elasticity of aggregates. This means that the mechanical properties of aggregates are not constant after the concrete has been cast.

Creep of concrete

The results of creep of concrete with alkali-sensitive aggregates showed, that the rate and magnitude of creep depends on ASR kinetics and the concrete age/maturity. In this context, it is important to know which factors influence concrete creep. There is a general agreement that creep of concrete has its source in hydrated cement paste but the physical nature and mechanism of creep are still not fully understood. Rossi et al. [27] study the physical mechanisms related to concrete creep. They proposed a physical mechanism for the origin of basic creep whereby basic creep is mainly, but not only, due to microcracking induced during creep loading. This means that microcracking in the cement paste caused by ASR can influence on creep behaviour of concrete. However, when the threshold of the reaction is attained, the creep magnitude decreases with time. This is due to the good curing conditions in the fog chamber (temperature and humidity). One can also assume that ettringite crystals grow into the cracks in the cement paste and increase the stiffness but, to a lesser amount, the strength. The study of [28] showed, that cracks are healed with ettringite crystals. The healed cracks with ettringite crystals and a crack width of approximately 30 μm are in the range of 10 μm up to 100 μm [28] for which the ettringite modification is not expansive but increases the stiffness [29].

One of the primary roles of aggregate in concrete is restraining of creep and shrinkage. There are certain physical properties of aggregate, which influence the creep of concrete. For a given cement paste and a given aggregate volume concentration, the stiffer the aggregate the lower the stress on the cement paste. Now, since creep of cement paste is proportional to the applied stress, the rate and magnitude of concrete is lower, the greater the elastic modulus of aggregate [30]. Therefore, it is concluded that not only the modulus of elasticity of concrete but also creep of concrete increases as the elastic modulus of the aggregate decreases. As mentioned above, it can be assumed, that the elasticity of concrete and creep behaviour of ASR damaged concrete is driven mainly by the damage of aggregate

5 CONCLUSION

The paper has reported on an experimental study with four concrete mixes. Compressive strength, static modulus of elasticity as well as creep and shrinkage deformations were measured. The concretes were made with four slow-reacting aggregates such as a greywacke, two quartz porphyries, and crushed gravel from the upper Rhine valley. The aggregates differ in their ASR sensitivity. The main conclusions are:

i) Any loss of mechanical properties is mostly driven by the damage in the aggregate particles and for a smaller part by the damage of cement paste.
ii) Static modulus of elasticity was significantly more affected by alkali-silica reaction than compressive strength.
iii) Compressive strength is driven by the microckracking in the cement paste.
iv) ASR reactive aggregates are unstable in high alkaline environments and undergo an alteration. This deterioration feature is irreversible and affects mechanical properties of concrete which depend on elastic modulus of elasticity of aggregates.
v) Static modulus of elasticity is mostly driven by damage (alteration) of the aggregates.
vi) The development of mechanical properties such as modulus of elasticity and compressive strength are very important to understand creep behaviour of ASR affected concrete.
vii) Creep of ASR affected concrete is driven by microckracking in cement paste and damage (alteration) of aggregates.

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TABLE 1: Development of compressive strength in MPa, (%).

Aggregate Type	Moist cabinet	Exposition time in the fog chamber in		
	28 days	140 days	280 days	560 days
OR	52,1 (100)	57,9 (111)	61,5 (118)	65,4 (125)
GW	50,6 (100)	69,2 (137)	71,4 (141)	72,7 (143)
QP	53,4 (100)	69,6 (130)	74,5 (140)	81,5 (153)
QP(SW)	54,5 (100)	72,5 (133)	74,2 (136)	83,8 (154)

TABLE 2: Development of the static modulus of elasticity in MPa, (%).

Aggregate Type	Moist cabinet	Exposition time in the fog chamber in		
	28 days	140 days	280 days	560 days
OR	37702 (100)	15805 (42)	20750 (55)	28934 (77)
GW	40302 (100)	43391 (108)	16440 (41)	25931 (64)
QP	36031 (100)	41078 (114)	41551 (115)	22342 (62)
QP(SW)	31729 (100)	38682 (122)	39543 (125)	40191 (127)

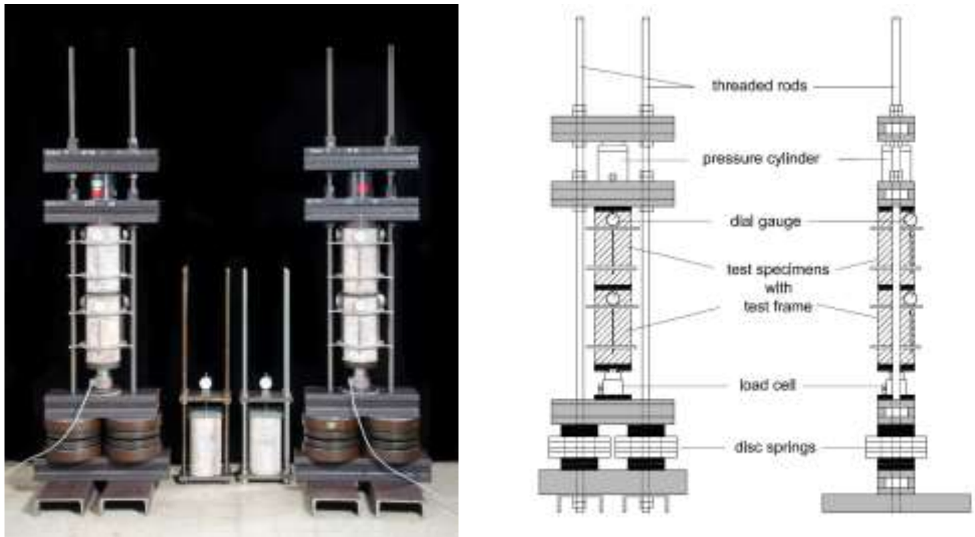

FIGURE 1: Test rig for compressive creep.

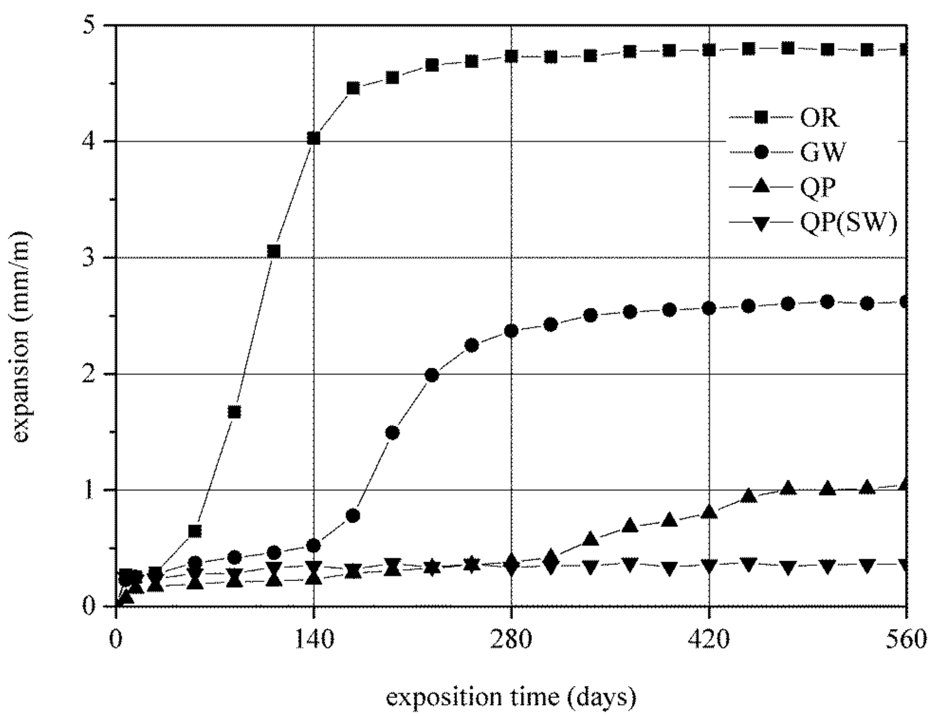

FIGURE 2: Expansion of concrete with OR, GW, QP and QP(SW) as aggregate.

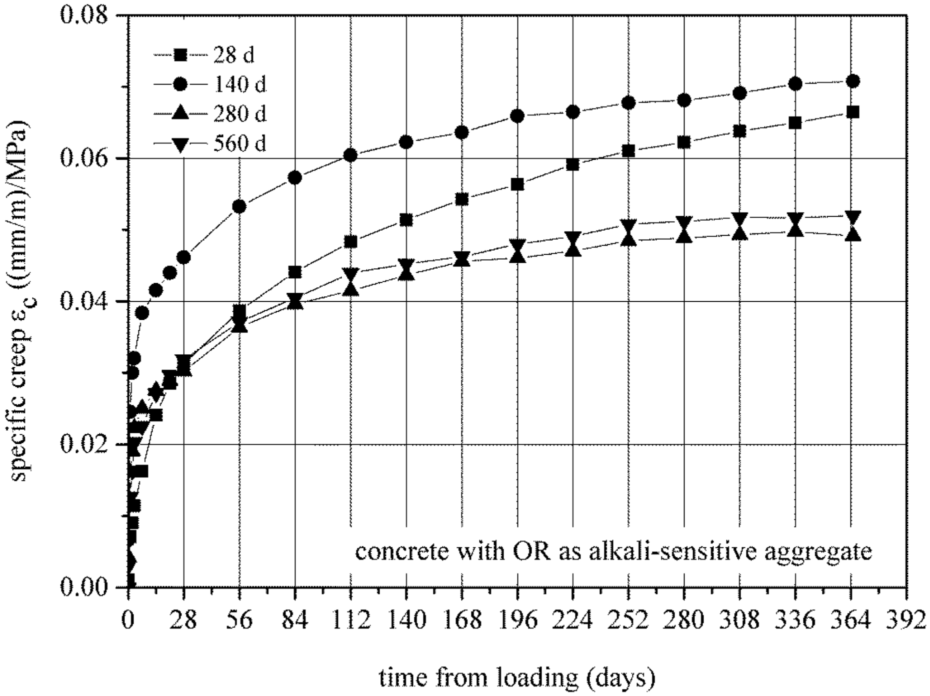

FIGURE 3: Time development of compressive creep of concrete with OR as alkali-sensitive aggregate, where loading ages are 28 days, 140 days, 280 days and 560 days, relative ambient humidity 80%.

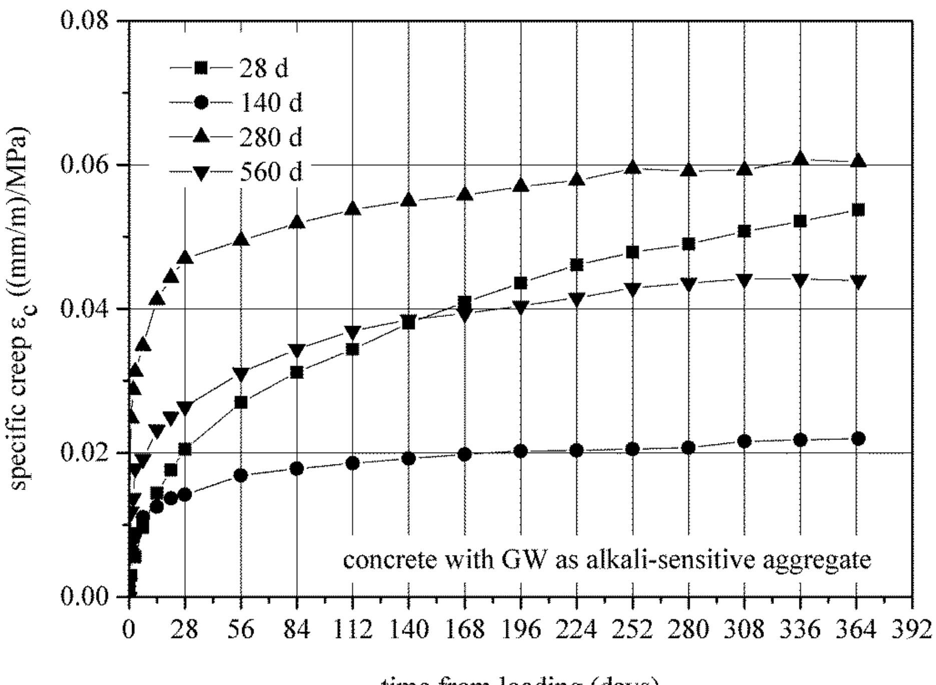

FIGURE 4: Time development of compressive creep of concrete with GW as alkali-sensitive aggregate, where loading ages are 28 days, 140 days, 280 days and 560 days, relative ambient humidity 80%.

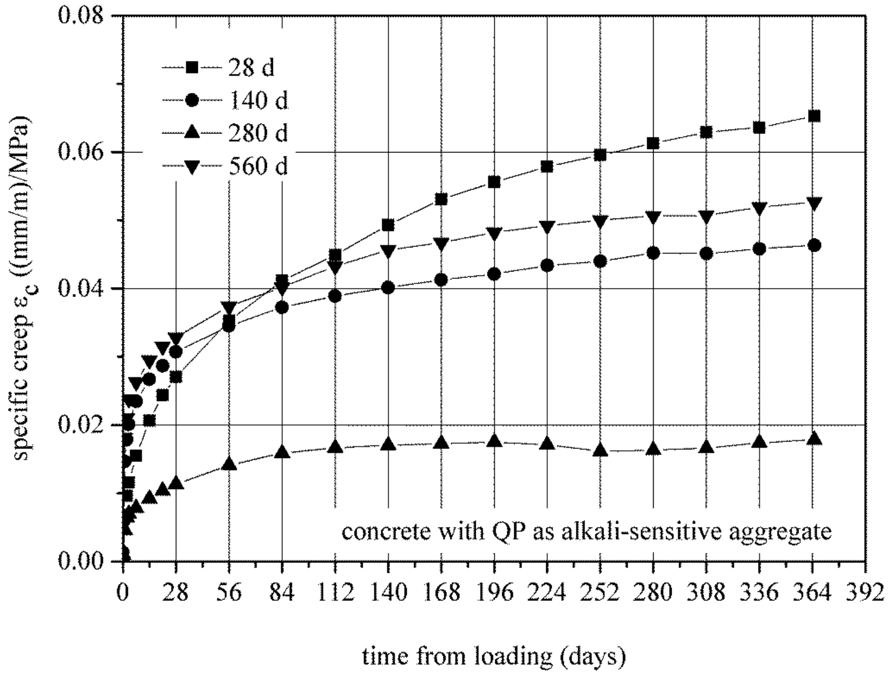

FIGURE 5: Time development of compressive creep of concrete with QP as alkali-sensitive aggregate, where loading ages are 28 days, 140 days, 280 days and 560 days, relative ambient humidity 80%.

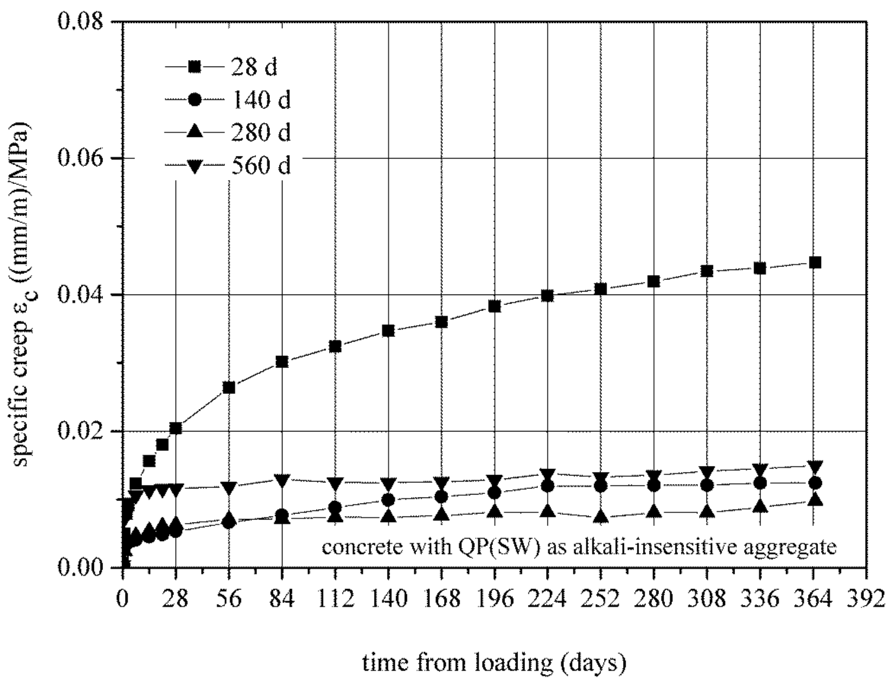

FIGURE 6: Time development of compressive creep of concrete with QP(SW) as alkali-insensitive aggregate, where loading ages are 28 days, 140 days, 280 days and 560 days, relative ambient humidity 80%.