Self-healing Behaviour of Ultra-High-Performance Concrete Under Constant Load

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Abstract. Concrete technology has been developing remarkably in recent decades. One of the most significant developments is the invention of ultra-high-performance concrete (UHPC), which can cope with the higher level of demands associated with complex structures, such as long-span bridges. The strength and durability of this type of concrete are quite high. However, this kind of concrete needs a very low water-to-cement ratio (up to 0.2); consequently, the hydrated cement particles could not exceed 26%. Hence, the cracks may appear frequently due to the autogenous shrinkage. To overcome autogenous shrinkage, a superabsorbent polymer (SAP) is used as an internal curing agent to subsequently increase the hydration of anhydrous cement particles. Much research has focused on inducing cracks under different curing conditions and observing the behaviour of the specimens when re-loaded, whether the cracks that had been induced had sealed during the curing time, and whether strength had been gained after re-loading. As such, in this research, a constant cracking load was applied to a pull-out specimen for 28 days under two different curing conditions (water curing and wet and dry cycles). The mix design for these specimens was UHPC with SAP of 0.3% and 0.4% of the total binder. Also, a reference UHPC mix has been used for comparison purposes. The results show that using SAP in the UHPC mix has the ability to boost the self-healing mechanism present in ultra-high-performance concrete. Additionally, tensile strength behaviour improved in the UHPC mix with 0.3% SAP.

Keywords: cracks · self-healing · superabsorbent polymer · ultra-high-performance concrete

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1 Introduction

During the last few decades, the improvement in concrete technology, namely, the capability to form concrete into different shapes, has promoted a significant consumption of the material in the construction of high raised complex buildings. The high performance of concrete with a relatively low cost has led to its wide range of applications. As such, concrete technology has been extensively developed in various aspects to align with the unique demands placed upon it. One of the most prominent technologies is the development of ultra-high-performance concrete (UHPC). Durability and high compressive strength are best features of UHPC, which enhance the mechanical performance of structural elements. UHPC has been used in many projects ranging from long span bridges to wind turbine towers [1–3]. However, there are still many challenges to overcome if UHPC is to be widely adopted.

Besides its considerable attributes, UHPC has an extremely low (water/cement) w/c ratio that can go up to 0.2. Consequently, the amount of hydrated cement can be limited to around 26% [4]. However, the low w/c ratio can cause high autogenous shrinkage leading to micro-cracking [5], which affects the safety and sustainability of the UHPC structural elements with pre-cracks. Even though collapse is less likely to occur due to micro-cracks, if they persist, it could lead to degrade the performance of these structural elements.

Cracks can be initiated due to loading or autogenous shrinkage, which affect the internal matrix of the concrete and pave the way for aggressive agents to enter inside the concrete. The increase of crack width leads to higher permeability for moisture and water flow [6] that accelerate the deterioration of concrete performance. Many design codes imposed a crack width limit; ACI 224R-01 [7] limits crack width up to 0.15 mm when concrete is exposed to wet and dry cycles. A traditional technique to limit crack widths is the use of adequate reinforcements as recommended by the design codes.

An improved hydration of cement particles within UHPC having an extremely low water/binder w/b ratio can be achieved by incorporating internal curing agents. The particles of these curing agents have a high water absorption capacity, which are released gradually. Light weight aggregates (LWAs) are often used in concrete without realising their ability for facilitating internal curing. Pre-saturated LWAs are found to be more effective than dried LWAs in terms of internally curing capability [8]. Henkensiefken [9] found that the pores in LWAs realise water to hydrate anhydrous cement particles at 96% of internal relative humidity (IRH); however, the water absorption capacity of LWAs is only about 5%–25% of their weight. This is contrary to superabsorbent polymers (SAPs), which have a much higher water absorption capacity that can reach up to 1000 times of their weight [10]. SAPs have mainly been used as internal curing agents to provide water to anhydrous cement particles after concrete is set [11–13]. SAP has also been investigated as an agent for forming sealing mechanisms in concrete [10, 11, 14].

Though SAP has been known to effectively reduce the autogenous shrinkage of UHPC, a limited number of experimental data exists on self-healing ability of UHPC using SAP [15]. Hence, the current study has aimed to investigate the effect of SAP particles in improving the healing capacity of concrete specimens under a constant load applied for 28 days.

2 Self-healing Technique

In this study, Portland cement, ground-granulated blast-furnace slag (GGBS), and silica fume were used in the concrete mix as the supplementary binder. Blended and dried sands with high silica contents (0.075 mm–1.18 mm) were utilised as fine aggregates, as they have sub-angular to rounded grains. In addition, tap water was used. A higher range of water reducer (HRWR) in the form of Polycarboxylates superplasticiser (SP), ViscoCrete-10 type, Sika, Australia was used to optimise the workability of the concrete. The HRWR used had 36% solid content by mass. Steel fibres (diameter: D = 0.2 mm, and length: L = 13 mm) having a tensile strength of 2500 MPa were used to reduce the crack opening through fibre bridging. The SAP used in the mix was Polyacrylate/Polyalcohol Copolymer that had the capability of water absorbing up to 60 g/g.

The details for the mix design of concrete are presented in Table 1 where UHPC refers to control mix, and S0.3 and S0.4 refer to mixes with two different proportions of SAPs. The proportion of water was adjusted to maintain the same level of workability as that of control mix. The workability was adjusted by increasing the amount of water and SP. Since SAP absorbs high quantity of water, a trial-and-error bases strategy was initially adopted to find the optimal mix prior to the full-scale of experimentation to achieve a proper level of workability by adjusting the content of SAP. For the preparation of concrete mix, the dry cementitious materials, sand, and SAP were first mixed at room temperature for 3 min. In next one minute, 90% of the water was added that is followed by mixing SP and remaining portion of water. The mixing continued for 25 min in wet state. Finally, the steel fibre was mixed for 3 min for a better distribution of the fibres.

Table 1. Proportions of concrete mix constituents

Mix ID	Binder		Silica fume (%) of binder	s/b	w/b	SAP (%)	Steel Fibre (%) (volume fraction)	SP (%)
	Cement (%)	GGBS (%)						
UHPC	85	15	25	1.1	0.166	0	1.5	4
S0.3					0.166	0.3		6
S0.4					0.17	0.4		6.5

Note: the binder contains the cement and GGBS only, s/b and w/b refer to fine aggregate to binder ratio and water to binder ratio, respectively, SAP (%) and SP (%) refer to the percentage with respect to the binder

2.1 Testing Methods

Determination of Mechanical Properties

The compressive strength of UHPC was evaluated according to AS 1012.9 [16] using cylindrical specimens. The modulus of elasticity was determined by attaching four strain gauges to the cylinders (two in the longitudinal direction and two in the transverse direction [17]). Tensile strength was determined by direct tension test of dog bone test specimens [18]. The flexural strength was evaluated according to [19].

Testing of Specimen Under Constant Load Condition

Specimens having a length of 500 mm and a square cross-section (75 mm sides) were cast and kept under ambient curing conditions (25 °C) for 28 days before commencing of their testing. Figure 1 illustrates the set-up for testing of these specimens. The idea was adapted from long term creep testing [20] of specimens under sustained loading with some modifications, made to measure the cracks near the mid-length of specimens, where the cross-section was provided a groove. The cracking load was applied for 28 days under curing conditions involving water curing as well as wet and dry curing cycles of two days cycles where conditions were changed constantly. The crack was initiated in the grooved area where the linear variable displacement transducer (LVDT) was attached. A strain gauge was attached to the threaded rod to measure the strain and convert it to the induced stress or load.

First, the specimens were loaded with a steady and gradual increase of the load until the first crack appeared. The load was then reduced to 50%, 60%, or 70% of the maximum load and the reduced load was sustained. The load adjustments were made manually to avoid any possible premature failure. Table 2 presents the different levels of loads and stresses, which have been extracted from the tension test. These load values were configured using the material property of the M16 threaded rod.

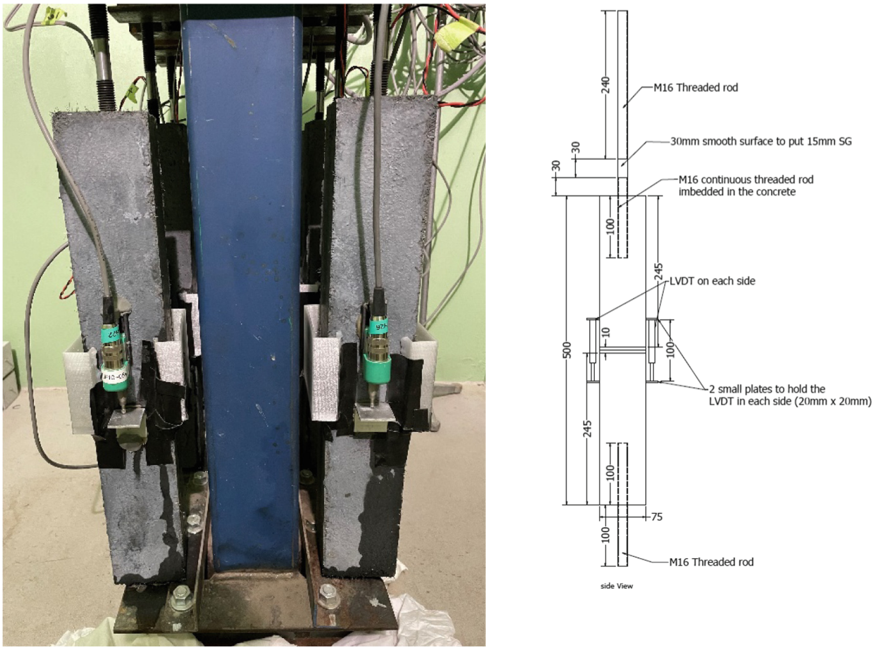

Fig. 1. Test set-up of specimens under constant loading

Table 2. Different levels of stresses and loads from tension test results

	UHPC	S0.3	S0.4
Stress at first crack (MPa)	4.50	4.90	3.84
Maximum stress (MPa)	4.62	5.10	4.14
Equivalent load from max stress (KN)	24.26	26.78	21.74
70% of the crack load (KN)	16.54	18.01	14.11
60% of the crack load (KN)	14.18	15.44	12.09
50% of the crack load (KN)	11.81	12.86	10.08

3 Results and Discussion

3.1 Mechanical Properties

Figure 2 has presented the influence of SAP on mechanical properties of UHPC as well as compressive strengths at 7, 28, 56, and 90 days for each concrete mix. The results show that the addition of SAP has negative influence on compressive strength in all cases. This effect was also reported in [21] and was linked to voids produced in the cement due to SAP. However, even though compressive strength was lower with the addition of SAP, it was found that the reduction in compressive strength at 7 days, which was about 13% lower than the control mix, was reduced to around 1% at 90 days.

The flexural and tensile strengths and modulus of elasticity values are also presented in Fig. 2 that shows S0.3% as the optimum mix, as it provided better results for the above-mentioned properties. Therefore, it can be stated that SAP has a positive effect on flexural and tensile strengths as well as elastic modulus that leads to stiffness enhancement of the mix. Similar findings were also reported in [22] for flexural and tensile strengths.

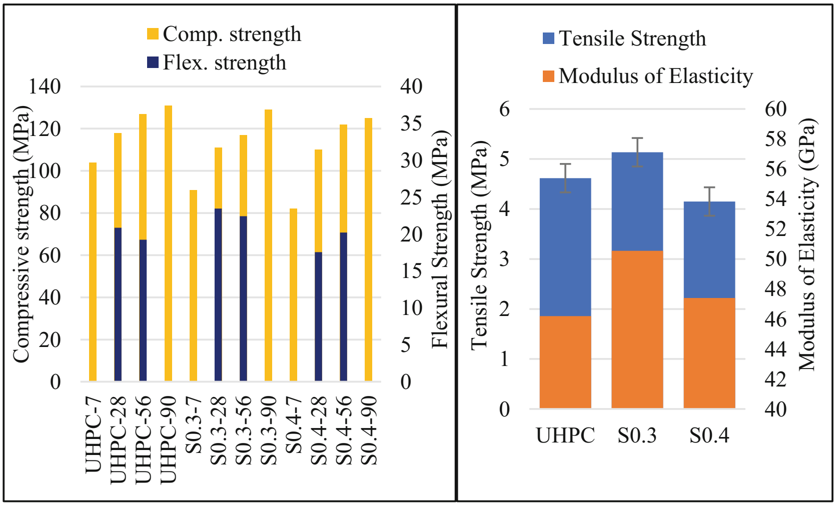

Fig. 2. Modulus of elasticity and compressive, flexural, and tensile strengths, the mix designated name is followed by number of days

3.2 Self-healing Under Constant Load

Wet and Dry Cycles

Figure 3 has presented time variations of displacements during wet and dry cycles where the displacement refers to the crack widening in the notched area. The average of two LVDT measurements was used to plot these results. For S0.4, the specimen was cracked on day 1. The stability of the curve (displacement or stress) means that there was no change in closing the cracks. For S0.3, the cracks were produced in a different area and the LVDTs couldn't record the crack widening. For the UHPC control mix, the load was applied slowly to avoid premature failure where the crack was produced in day 9. For all specimens except for the UHPC specimen, displacement remained relatively stable during the testing. The displacement of UHPC specimen increased slightly after day 7; the increase was attributed to the load applied occasionally to initiate cracks.

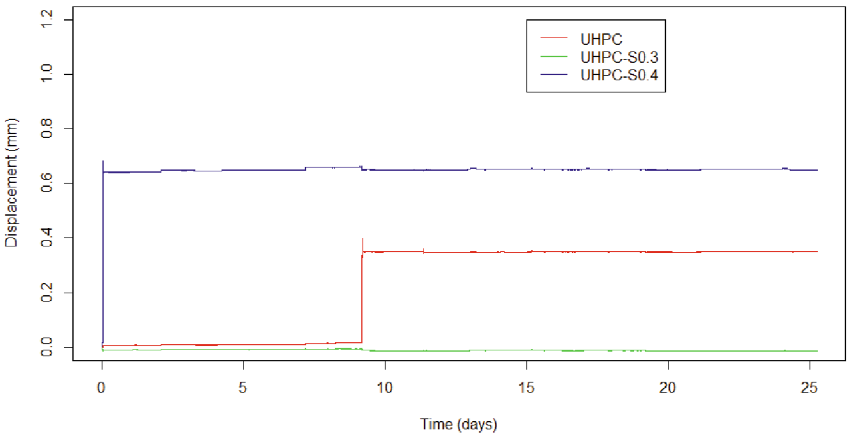

Fig. 3. Time variations of displacement during wet and dry cycles

Figure 4 has presented the time variations of stresses duration the test where the load was applied periodically to reach the cracking load. For S0.4, the stress was approximately 8 MPa on day 1, which was then reduced to 2 MPa, i.e., 50% of the cracking load according to the tensile strength results. The stress was increased occasionally on days 1, 3, 5, 7, and 9. After day 9, the stress remained around 50% of the cracking load for 15 days. It is evident that the stress was increased during this period. The reason for this is the healing of S0.4 to the increase of stress rather than the decrease of displacement.

For S0.3, the specimen was loaded up to 8 MPa to reach the cracking load on day 9. Subsequently, the failure occurred, and the measurements could not be taken, as mentioned earlier. For the UHPC control specimen, the load was boosted on the same days as that of S0.4, and the crack was initiated on day 9. The load was adjusted on day 12 to reach 50% of the cracking load. After day 12, the load remained constant, which means that the capacity of the specimen was not increased. As can be seen, S0.4 produced the best results in terms of crack healing and recovering stiffness at same displacement obtained from for the wet and dry cycles.

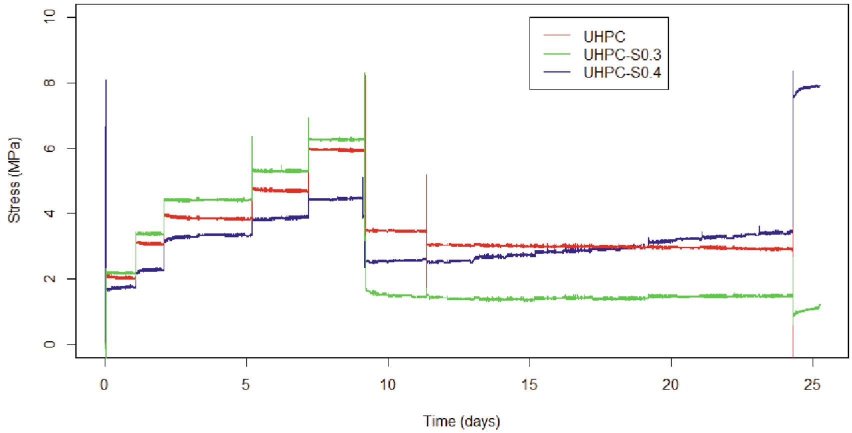

Fig. 4. Time variation of stress during wet and dry cycles

4 Conclusions

The UHPC control mix and mixes with addition of SAP having 0.3% and 0.4% of the binder were investigated. The mechanical properties of these mixes were first measured and processed before testing notched specimens under constant tensile loading during wet and dry cycles. Based on the experimental observations, the following conclusions can be made:

- The addition of SAP has insignificant effect on the compressive strength of UHPC but shows long-term improvement - reaching 99% of the strength of UHPC after 90 days.
- Flexural and tensile strengths were improved by adding SAP to the mix where S0.3 showed optimum improvement.
- For specimens under constant tensile load, S0.4% proved the best stiffness recovery by means of increase in the stress values.

This study employed a novel concept for testing the notched specimens under constant tensile loading that provided a wider range of valuable results. As can be seen, it also provided results that were more reliable as they can simulate real situations. For future studies, the same test procedure can be followed, but the curing conditions can be varied to simulate aggressive environments. It would also be of useful to study the long-term effects by increasing the duration of test up to 180 days, which would allow to investigate the effect of creep.

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