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Compressive strength of concrete after early loading

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In modern construction projects it is necessary to work with concrete at a time before its strength can be fully developed. Applying large construction loads to a structure can lead to a reduction in strength if the serviceability limit has been exceeded. However, the effects of smaller compressive loading on concrete cubes, below the serviceability limit state, have been found to have a positive impact on the 28 day ultimate strength. The results from this study indicate the 28 day strength of wet cured concrete cubes increased on average by 6% when specimens were loaded up to 90% of their ultimate strength at 1, 3 or 7 days after casting. Concrete specimens under the same conditions loaded past the point of maximum stress at an early age displayed a reduction in strength from 5% or greater, depending upon the extent of the loading. This phenomenon of increased strength after loading and subsequent curing has been reported in the literature for many years, but the use of modern compressive test apparatus has enabled the present authors to show that the final strength has a high level of correlation with the displacement during the initial early loading. The experiments carried out in the present study were to simulate high construction loading at early ages to better understand the effects of early loading and the changes in ultimate strength at later age.

1. Introduction

Construction loading is often the most intensive stage of a structure's life, with the concrete still in its early stages of strength development it is essential to ensure it is not overloaded. Premature removal of formwork, lifting or moving of precast concrete or large construction live loads can cause cracking or other damage (Kaminetzky and Stivaros, 1994). Even if a structure does not collapse during the construction stage, it is possible to damage it and reduce its strength. The aim of this study was to examine the effects of compressive loading of concrete at stages typical in the use of the shoring/reshoring technique, widely used in concrete floor construction in multi-storey buildings, where concrete can undergo large compressive strengths soon after casting.

In this study, 100 mm concrete cubes were compressed to loads of 70, 80 and 90% of their ultimate strength to simulate early overloading at 1, 3 and 7 days after casting, which is typical of early stages in construction of concrete structures. These specimens were reloaded at 28 days after being wet cured under laboratory conditions. Comparing the results from early loaded specimens and control specimens, an increase in strength was recorded for most, although not all specimens. This study went on to further examine the relationship between the increase in strength and initial loadings of specimens and found some correlation between the initial displacements of specimens and the gain in strength.

This minor gain in strength can give confidence to designers and contractors, because it shows that early loading is not as damaging as they might have expected. The authors are not, however, suggesting that the observed additional strength should be relied upon in designs or that deliberate early loading should be used to try to obtain it.

This phenomenon was also found in the literature in similar studies of sustained biaxial loading, long-term creep and re-testing loaded specimens over different periods. The results of wet-cured specimens from a published paper were recalculated to find a similar result to the one found here.

2. Literature review

Concrete under uniaxial loading will develop cracks parallel to the direction loaded. Under uniaxial loading from 30% to around 70% of maximum stress, the concrete will undergo slow crack propagation. At between 70 and 90%, cracks will begin to increase noticeably (Santiago and Hilsdorf, 1973). Fine cracks that have been created in fractured concrete are capable of complete recovery under moist conditions; this is aided by the formation of insoluble calcium carbonate from the calcium hydroxide in hydrated cement (Neville, 1994). The process of cracked concrete undergoing self-repair is known as autogeneous healing.

From earlier studies, the phenomenon of autogeneous healing was found to heal cracked specimens to strengths almost equal to unloaded specimens, provided the specimens were not badly shattered and were subject to continuous moist curing (Gilkey, 1926). Autogeneous healing was first recognised by Abrams in 1913 (Whitlam, 1954) where cracks disappeared in a highway bridge 3 years after their appearance. To quantify autogeneous healing, reloading times have ranged from 3 days to 10 years in a range of different studies since its discovery. In 1950 a study of 10·5 year old concrete specimens under sustained creep conditions were reloaded to examine the effects of long-term creep (Washa and Fluck, 1950). Reloaded specimens displayed 'about 5% higher [compressive strength] for hand-rodded concrete, than that of companion unloaded cylinders'.

Abdel-Jawad and Haddad (1992) carried out tests which were similar to those reported here and concluded that 'loading concrete, beyond 8 h of casting, up to 90% of its compressive strength [at time of loading] has no effect on the strength of concrete at a later age'. Loading concrete past maximum stress (i.e. to failure) resulted in a strength loss of from 10 to 50%, depending on the age at time of loading, the age at time of re-testing and the curing conditions.

Upon re-examination by the present authors of the research done by Abdel-Jawad and Haddad (1992) in which 900 specimens were loaded 8 to 72 h after casting, and reloaded between 7 and 90 days, it was found that under certain conditions the crushed specimens displayed greater strength development against specimens not previously loaded. The experiment focused on re-testing concrete with different water/cement (w/c) ratios at 7, 28 and 90 days under both wet and dry conditions. Figure 1 is taken from their data collected for wet cured specimens with a w/c ratio of 0·7 showing the strength ratio of specimens previously loaded against control specimens.

Under the conditions of: (1) initial loading taking place after 8 h of casting; (2) the load being less than 100%; and (3) the age of re-testing being 28 days, it was found that the majority of specimens displayed a substantial increase in strength averaging 5·7% above that of the control strength (Figure 2). This does not conform to typical theoretical models regarding autogeneous healing of specimens, where specimens are only expected to regain up to their original strength (Neville, 1994).

Coutinho (1977) suggested this is due to a factor of creep; 'pressure, like temperature, influences chemical reactions, particularly the reaction of the cement components with water. The pressure to which cement components are submitted increases their solubility in the water with which they are in contact, thus increasing the hydration of cement'. It has also been suggested that this increase in strength is greater when applied to younger age concrete for longer durations of loading, although it has been noted by Coutinho that the increase in compressive strength does not exceed 15%.

A study from 2002 (Liu *et al.*, 2002) in which crack restoration under sustained biaxial compression (30% of ultimate strength over period of 14 days) also found this phenomenon of increased strength for specimens subject to compressive loading. It was concluded that, 'Concrete creep deformations will not definitely cause damage of the material. On the contrary, the sustained compression load at an early age can increase the strength'. Similarly to work done by Abdel-Jawad and Haddad (1992) the increase in strength was most prominent around 4 weeks after casting, becoming less prominent at later ages. Results from their study also indicate that sustained biaxial loading caused greater strength increase than uniaxial loading alone (Table 1).

3. Experimental procedure

Cement class CEMII/A LL 32.5R to BS EN197 (BSI, 2000) was used to create three different mix designs with 10 mm uncrushed stone and fine crushed aggregate 50% passing through the 600 μm sieve (Table 2).

The 100 mm concrete cubes were made to BS 8500-1:2006 (BSI, 2006) and tested to BS EN 12390-3-2009 (BSI, 2009) at 1, 3 and 7 days up to their designated loads of 90, 80 and 70% of the ultimate load. An average of two control specimens were used for each variable to find the relevant percentage of ultimate loading for the test. Two replicate specimens per variable were loaded up to their relevant values at a uniform rate of 0·1 N/mm^2 per s and immediately released.

In addition to the standard test a linear displacement transducer was used to record the displacement during testing. The apparatus recorded the load and displacement at 0·1 s intervals. A correction factor derived from calibration tests was

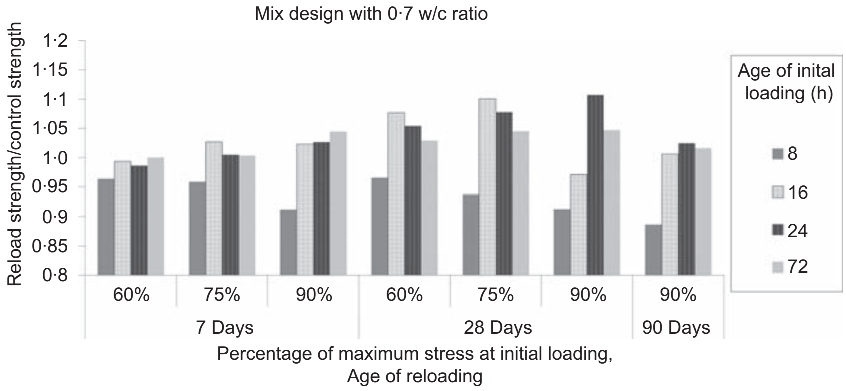

Figure 1. Reload strength ratio of wet cured concrete specimen with 0·7 w/c ratio from Abdel-Jawad and Haddad (1992)

used on the displacement readings to account for machine stiffness.

The specimens loaded to failure were loaded until a drop of 50 kN strength was recorded; this was to accommodate local failures in specimens. The hydraulic pressure in the test machine was applied with a very sensitive computer-controlled pump which was able to release the load exactly when the 50 kN decrease occurred.

These specimens were stored for later reloading along with specimens loaded to their designated fraction of the ultimate strength.

All specimens were stored in a curing tank after 24 h of setting (20 ± 2°C) until the 28 day tests.

At reloading, all specimens were compressively loaded on the same axis up to failure. The results were compared with three or more control specimens to give a proportion of the control strength/reload strength for each mix design, intensity of initial load and age of specimens.

4. Results

Specimens loaded to 90% or below showed little or no visible cracking to the naked eye. Loading specimens beyond this to the point of failure resulted in fast crack propagation and with continued loading specimens were destroyed beyond the point of re-test.

When specimens were initially loaded between 70 and 90% of their ultimate load the results indicate an increase in strength averaging between 0·9 and 7·8% per mix design (Figure 2). This was most prominent in mix 3 resulting in some specimens reaching an increase of 14·7%, although this increase was visible in almost all specimens used in this experiment.

Specimens loaded to beyond the point of failure showed prominent signs of cracking and a marked reduction in re-test strength at 28 days.

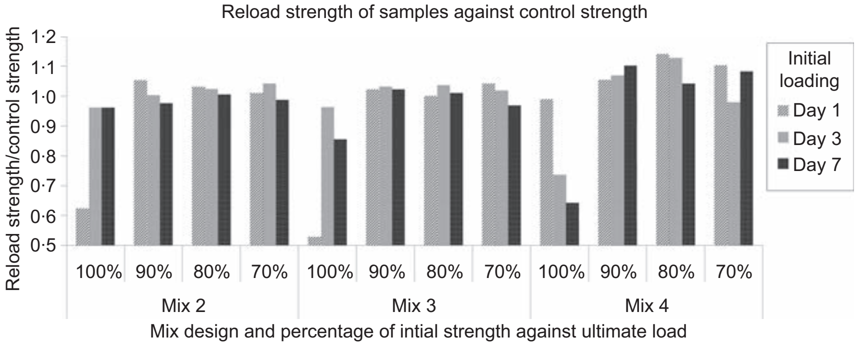

Figure 2. The reload strength of specimens loaded to a percentage of the ultimate strength at time of loading

Creep type, stress levels: % of ultimate strength	Load age: days	Load duration: days	Strength of creep specimens: MPa	Strength of non-creep specimens: MPa	Strength of creep specimens/non-creep specimens: %
Biaxial 30%	14	45	–	8·2	–
Biaxial 30%	60	90	14·4	11·3	27·4
Biaxial 30%	30	28	10·8	5·5	96·4
Biaxial 30%	60	30	10·7	7·0	52·9
Uniaxial 30%	60	12	19·7	18·3	7·7
Uniaxial 60%	90	18	19·8	20·9	−5·3

Table 1. Biaxial and uniaxially loaded concrete on re-testing at varied ages (Liu *et al.* 2002)

The extent of the initial loading, except for specimens loaded up to failure, did not appear to have any relation to the increase in strengths between 70 and 90%. It was found that the relationship between the increases in strength depended more upon the extent of deformation of specimens (Figure 3).

Figure 3 shows the increase in 28 day reload strength to be most prominent when specimens were initially deformed to around 0·3 mm, many specimens still displayed an increase in strength typically up to 1 mm. However, after a deformation past the threshold of 0·3 mm some specimens lost strength through excessive cracking beyond which autogeneous healing could not take place. Past the threshold of 0·3 mm a large drop in strength was seen in some specimens showing a disparity between concrete strengths where failure has taken place.

When re-testing specimens previously loaded past maximum stress with a 50 kN recorded drop in load after failure, it was seen that most specimens were subject to a noticeable reduction in strength, in some cases this was seen to be up to 50%. To study this in greater detail, additional tests were carried out on mix 3 specimens by loading them at 1 day after casting to varying degrees past ultimate failure. The reduction of strength was determined to have a relationship to the extent that a specimen was loaded past failure (Figure 4).

5. Discussion

Specimens loaded past the point of failure underwent fast crack propagation close to the ultimate load, at around 90 to 100%. The crack widths after overloading were generally too great for autogeneous healing to take place. The extent to which specimens were loaded past the point of maximum stress had a significant impact on the strength development of the specimens. As expected, once a specimen reached maximum stress, any further loading resulted in a greater loss in reload strength.

When specimens were loaded up to 90% of maximum stress at an early age, an increase in strength relative to control specimens was recorded. The findings in this study found that initial loadings between 70 and 90% increased the strength of specimens by between 0·9 and 7·8%. This phenomenon is reinforced by work by Coutinho (1977) and Abdel-Jawad and Haddad (1992) and where concrete loaded under similar conditions of 28 day re-testing and wet curing conditions showed signs of increased strength. Work by Liu *et al.* (2002) also emphasises that the strength of concrete is increased through both biaxial and uniaxial compressive creep, provided the strength is below 30% whereas sustained loading above this may lead to slow crack propagation, leading to excessive cracking and failure over time.

The strength increase found in this paper reinforces the theories put forward by Coutinho (1977) where hydration of cement components is increased due to their solubility in water with which they are in contact. The increase in strength from the experiments rarely exceeded 15%, as concluded by Coutinho as the maximum gain in strength from compressive

Mix no.	Cement: kg/m^3	Water: kg/m^3	w/c ratio	Coarse aggregate: kg/m^3	Fine aggregate: kg/m^3	Slump: mm
1	450	225	0·5	863	863	150
2	456	205	0·45	616	963	110
3	585	205	0·35	815	815	110

Table 2. Mix proportions used in experiments

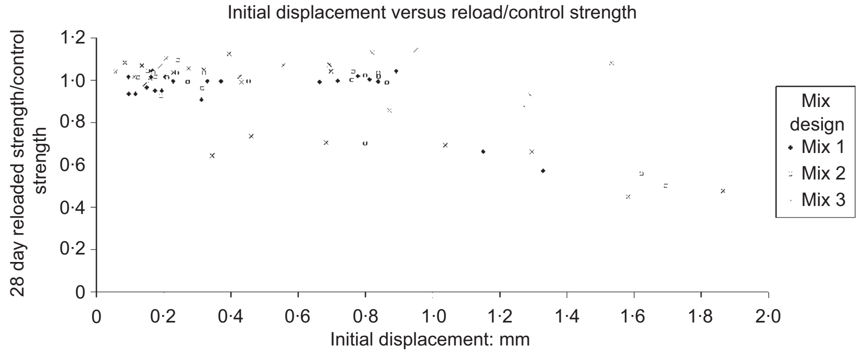

Figure 3. Reload strength of specimens against displacement at initial loading at early age

loading. However, the results found by Liu *et al.* (2002) suggest that concrete strength can be increased a great deal further than by increased hydration alone, where sustained biaxial loading at 30% increased the reload strength by 96%.

The increase in ultimate strength in concrete after creep compared to concrete that has not been submitted to permanent loads is well documented. Short-term loading of early age concretes at higher stresses can also lead to an increase in strength up to 15% showing that concrete strength development can be possible without long-term creep.

The increase in strength was found in the present study to have some correlation with the extent to which specimens were displaced when initially loaded. After a displacement of 0·3 mm, some concrete specimens were seen to show a large reduction in strength as cracks propagated parallel to the loading. However, some specimens continued to show an increase in strength up to 1·0 mm displacement.

The authors must stress that the increase in strength found in this paper and similar work occurred under laboratory conditions. Although this may provide some comfort to designers and contractors it should in no way be taken into account when designing or constructing structures. All specimens in this experiment were wet cured and this paper does not make a correlation between wet-cured and dry-cured specimens, which may have different, possibly negative, effects in practice.

6. Conclusion

Over 100 concrete cubes were tested to study the effect of static uniaxial compressive loading on the strength development at 28 days. From the results the following conclusions have been drawn.

(*a*) Loading specimens to failure at early ages reduces the strength at 28 days.
(*b*) The reduction in strength of specimens is dependent upon

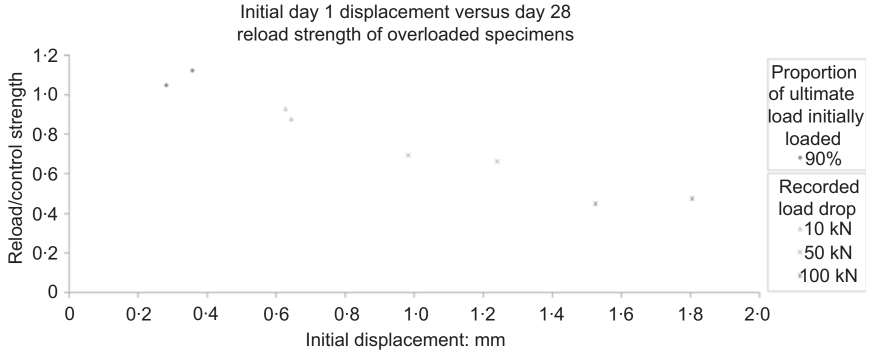

Figure 4. Drop in reload strength at 28 days of specimens of mix 3 loaded past failure 1 day after casting

the extent to which the specimen has been loaded after failure.

(*c*) Specimens loaded between 70 and 90% of their ultimate load between 1 day and 7 days exhibited an increase in strength at 28 days after casting.

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