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# EFFECT OF INITIAL CURING ON EARLY STRENGTH AND PHYSICAL PROPERTIES OF A LIGHTWEIGHT CONCRETE

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**ABSTRACT**

A 50 MPa 28-day cube compressive strength structural lightweight concrete of a fresh concrete density of 1800 kg/m$^3$ was produced using Lytag coarse and fine aggregate. The long-term strength development and the durability characteristics of this lightweight concrete are being monitored in both the severe hot and dry and hot-coastal and salt-laden exposure conditions prevalent in Kuwait. The early results of the investigation suggest that the compressive strength of this concrete is less sensitive to lack of initial curing. However, depth of water penetration, which is indicative of the concrete's permeability and hence durability, has been found to be more sensitive to the duration of initial curing even for the specimens exposed to the high-humidity seaside ambient conditions. The drying shrinkage of this concrete has been found to be more than 600 microstrain in the first 3 months' duration. Longer term durability data will be reported in due course. © *1998 Elsevier Science Ltd*

## Introduction

High performance concrete (HPC) is now a well-developed construction material. HPC possesses medium to high strength and has superior volume stability and durability characteristics. In addition, HPC is now available as normal weight concrete (NWC) and structural lightweight concrete (SLWC). Whilst the availability of NWC-HPC is almost universal, the utilisation of SLWC is also on the increase. SLWC has its obvious advantages of higher strength/weight ratio, better tensile strain capacity, lower coefficient of thermal expansion, and superior heat and sound insulation characteristics. However, a more uniform and less variable manufactured lightweight aggregate (LWA) is required for the production of SLWC. Accordingly, the initial unit cost of the SLWC is higher, and its cost will be almost prohibitive where manufactured LWA is not available locally. Nonetheless, for some off-shore structures, the use of SLWC is almost essential and in many countries the manufacturing of LWA is being considered actively. The other benefit of LWA is its environmental enhancement. Almost without any exception, LWA is being manufactured from industrial by-products such as fly ash, expanded slag and/or municipal sludge.

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TABLE 1
Mix proportions and characteristics of fresh concrete.

| Material | Mix quantities ($kg/m^3$) | Properties of Fresh Concrete |
|---|---|---|
| Cement (similar to ASTM Type 1) | 500 | Initial slump = 90 mm |
| Condensed silica fume | 50 | Slump after 10 min. = 65 mm |
| LYTAG course aggregate (oven dried) | 528 | Unit weight = 1815 $kg/m^3$ |
| LYTAG fine (oven dried) | 333 | Air content = 1.7% |
| Water (total) | 274 | Temperature = 25°C |
| Superplasticiser = 1.2%, by weight, of cement | | |

Both NWC and SLWC are capable of serving their intended use in structures when properly designed, specified and manufactured (1). Nonetheless, the durability performance of SLWC is not as well researched and reported as that of NWC (2–4). Accordingly, a research project was undertaken to ascertain the durability characteristics of a 50-MPa SLWC in the severely hot, coastal and salt-laden ambient conditions prevalent in Kuwait. This paper reports the strength and some physical characteristics of the concrete upto a period of 3 months.

## Experimental Program

A high-strength structural lightweight concrete (SLWC) using Lytag LWA was made to evaluate its strength and durability characteristics. A few initial trials were made to optimise the mix to obtain a slump of about 100 mm, fresh unit weight of 1800 $kg/m^3$ and 28-day cube compressive strength of approximately 50 MPa.

The Lytag coarse, 12 mm, and Lytag fines were soaked and mixed with about 1/3 of the mixing water for approximately 10 min. in the pan mixer. Thereafter, cementitious materials and the mixing water were added. The superplasticiser, admixed with about 1 kg of water, was added towards the final mixing stage. The slump, unit weight, air content, and the temperature of the fresh concrete were determined. Another slump measurement was made 10 min. after the first one to determine the slump loss.

The mix quantities used and the properties of the fresh concrete are included in Table 1. In all, 37 batches of concrete were made; the properties included in Table 1 are the average value, and their range is included in Table 2.

TABLE 2
Variation in the properties of fresh concrete.

| Test | Minimum | Maximum | Average |
|---|---|---|---|
| Initial slump (mm) | 80 | 95 | 90 |
| Final slump (mm) | 50 | 65 | 65 |
| Unit weight ($kg/m^3$) | 1800 | 1820 | 1815 |
| Air content (%) | 1.4 | 1.8 | 1.7 |
| Temperature (°C) | 24 | 26 | 25 |

### Specimens Cast

The following specimens were made in this investigation:

1. 105–100 mm cubes for compressive strength evaluation;
2. 48–100 × 100 × 500 mm beams to determine modulus of rupture;
3. 72–150 × 300 mm cylinders for indirect tensile strength and modulus of elasticity;
4. 42–200 × 200 × 120 mm slabs to determine depth of water penetration;
5. 10–150 × 150 × 750 mm beams to determine compressive strength of cores and depth of carbonation;
6. 6–50 × 50 × 285 mm prisms to monitor drying shrinkage.

### Initial Curing and Exposure Regimes

The specimens were initially cured as given below:

- Full curing: Curing in water tank maintained at 23 ± 2°C till the age of testing;
- 1 day curing: No water curing after demolding;
- 3 day curing: Curing in water tank for 2 days after demolding;
- 7 day curing: Curing in water for 6 days after demolding.

In addition to the continuous water curing, specimens were placed on the rooftop of the concrete laboratory and an exposure site near the sea at a Yacht Club after different curing regimes.

The relevant British Standards (5,6) were used to evaluate strength characteristics of the concrete. Permeability of concrete to water was determined by DIN 1048 Part 1 (7). This test was performed on plate-shaped test specimens of 200 × 200 × 120mm. The test takes 4 days for completion. At first a pressure of 1 bar was applied for 24 h, then pressures of 3 and 7 bars, each for 24 h. Immediately after the test, the plate was split in the middle and the greatest water penetration depth and its distribution were measured. The depth of carbonation was determined using phenolphthalein indicator. Cylindrical cores of 100 mm diameter were extracted from 150 × 150 × 750 beams according to BS 1881: Part 120 (5). The results are an average value of 3 or a minimum of 2 tests and are included in Table 3.

## Results and Discussion

### Properties of Fresh Concrete

The concrete batches made were very cohesive and workable. The maximum value of the unit weight of the fresh concrete was 1820 kg/m$^3$ with an average of 1815 kg/m$^3$. If one takes the unit weight of normal weight concrete (NWC) as 2400 kg/m$^3$, there is about 32% saving in the self weight. Although the aggregates were presoaked for about 10 min., there was still, on the average, a slump loss of 25 mm in the 10 min. after completion of mixing. There was no requirement of air-entrainment, and the average air content of the concrete was 1.7%. The concrete specimens looked somewhat darker than the NWC.

TABLE 3
Strength and physical characteristics of SLWC.

| | Water Cured | | Roof Top | | | | | | Seaside 28 Day Strength | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 1 Day Curing | | 3 Day Curing | | 7 Day Curing | | | | |
| | 28 Day | 91 Day | 28 Day | 91 Day | 28 Day | 91 Day | 28 Day | 91 Day | 1 Day Curing | 3 Day Curing | 7 Day Curing |
| Compressive strength 100 mm cube (MPa) | 51.0 | 55.8 | 48.2 | 46.8 | 50.2 | 48.9 | 55.0 | 53.8 | 51.5 | 55.9 | 60.7 |
| Indirect tensile strength 150 × 300 mm cylinders (MPa) | 3.30 | 3.70 | 3.20 | 3.25 | 3.40 | 3.45 | 3.55 | 3.70 | 3.15 | 3.45 | 3.60 |
| Modulus of rupture 100 × 100 × 500 mm (MPa) | 4.40 | — | 3.65 | — | 3.85 | — | 4.05 | — | 4.00 | 4.30 | 4.35 |
| Modulus of elasticity 150 × 300 mm cylinders (GPa) | 26.1 | — | 25.4 | — | 26.0 | — | 26.3 | — | 26.3 | — | 26.9 |
| Water Penetration (mm) 200 × 200 × 120 | 19.6 | | 36.0 | | 29.1 | | 26.8 | | 38.2 | 32.0 | 28.6 |
| Depth of carbonation (mm) 100 × 100 × 500 beam | | | 1.0 | 4.0 | 0.3 | 1.7 | 0.0 | 1.0 | 0.7 | 0.3 | 0.2 |

## Compressive Strength

The 28-day cube compressive strength of water-cured concrete is 51 MPa, whereas the 91-day is 56 MPa. There is only a 9% increase in strength in a period of 2 months. This value is typically less than that for NWC. Of course, the strength development in lightweight concrete is limited by the inherent strength of aggregate. Kayyali and Haque, using the same lightweight aggregate and somewhat similar mix proportions with a further addition of 192 kg of flyash, produced a SLWC of 67.5 MPa 28-day cylinder strength (8).

The effect of different early curing regimes on compressive strength can be seen in Table 3. The two salient features worth noting are: First, up to 28 days, lack of curing (1 or 3 day initial curing only) does not seem to have a noticeable effect on the strength as compared to the strength development of the continuously water cured cubes. This is attributable to the internal reservoir of water, which is stored in porous lightweight aggregate particles. This internal water keeps the hydration process going. However, at the age of 91 days, i.e., after prolonged exposure of specimens at the rooftop, the effect of lack of curing has an effect on the strength development. The 91-day strength of 1- and 3-day cured cubes is 16 and 12% less than the corresponding strength of the fully cured cubes. Again, the adequacy of the initial 7-day curing on the strength development can be seen in Table 3. The strength of the 7-day cured cubes is very similar to that of the continuously cured cubes. These results are comparable to those of the NWC as reported earlier (9,10).

The specimens stored at the seaside gave a higher 28-day strength after 1, 3, and 7 days of initial water curing than the specimens continuously cured in water. One possible explanation for this is that the sufficiently high ambient humidity and temperature prevailing at the seaside accelerated the rate of hydration, and hence the resultant higher strength. Again, the first 7 days' initial water curing and subsequent sea exposure (tropical conditions) resulted in a 19% higher strength than the strength of continuously water- cured specimens. The future long-term comparative strength of the continuously water- and seaside-exposed specimens will be of great interest.

**Indirect Tensile Strength**

The indirect tensile strength of the continuously water-cured concrete is 3.30 and 3.70 MPa at 28 and 91 days, respectively (see Table 3). These values are only 6.5% of the corresponding cube compressive strengths. As reported by other researchers (11,12), the tensile strength of SLWC is less than the tensile strength of the similar strength grade NWC.

The effect of lack of curing on the indirect tensile strength, as shown in Table 3, is somewhat similar to that on the compressive strength. Again, 7 days of initial water curing and subsequent storage on the rooftop resulted in no loss in the tensile strength at the age of 91 days. Likewise, up to a period of 28 days, seaside exposure seems to have enhanced the tensile strength after an initial curing of 3 and 7 days as compared to the strength of the continuously water-cured concrete.

**Modulus of Rupture**

Modulus of rupture value of 4.40 MPa is only 8.6% of the compressive strength, which is approximately 50% of the value for the NWC (13). For a similar but higher strength SLWC, Kayyali and Haque (8) have reported a value of 8.3%.

Modulus of rupture of both NWC and SLWC is known to be more sensitive to lack of curing and the moisture gradients than compressive strength (14,15). The results shown in Table 3 corroborate this.

**Modulus of Elasticity (*E*)**

The *E* value of the concrete at 28 days is about 26 GPa under the differing curing regimes adopted in this investigation (Table 3). Perhaps the presence of inner reservoir of water in the porous aggregate particles and the resultant ongoing hydration, irrespective of the exposure conditions, has not caused any degrading effect on the *E* value. This value, of course, is comparatively less than that for a similar strength NWC (11).

The calculated value of *E*, using the ACI (16) or the AS-3600 (17) expression of:

$$E_c = 0.043\rho^{1.5}\sqrt{f_c}\ \text{MPa}$$

is 23.7 GPa. In the ACI and AS-3600 codes, $f_c$ is the cylinder compressive strength. The above value of 23.7 GPa was obtained using cube strength value of 51 MPa. If the cube strength were converted into equivalent cylinder strength, the estimated value of $E_c$ would be even lower than 23.7 GPa. Using the British Standard (18) expression of:

$$E_c = 1.7\rho^2 f^{0.3}$$

TABLE 4
Water penetrability of the concretes tested.

| Concrete Type | 28 day Cube Strength (MPa) | Depth of water penetration (mm) |
|---|---|---|
| SLWC | 51 | 19.6 |
| NWC | 46 | 21.5 |
| NWC | 40 | 23.0 |
| NWC | | 51 |
| Sitemixed—site cured | 23.5 | |
| Sitemixed—lab cured | 26.5 | 48 |

an $E_c$ value of 18.2 GPa was obtained. Of course, in the above expression $f$ is the cube strength. Similarly, the Norwegian Standard (19) gave a value of $E_c$ of 20.3 GPa.

Also, in all the above calculations the value of $\rho$ used was the fresh density rather than the air dry density of the concrete, which is the value normally used. The air dry density of the concrete could not be monitored in this investigation.

More often than not, the code formulae are reported to overestimate the $E$ value of high-strength structural lightweight concretes (11,19). However, for the concrete reported here the calculated $E$ values using code formulae are less than the observed value. In this investigation, a better esitmate of the $E$ value of 23.7 GPa against an experimental value of 26 GPa has been obtained using the ACI (16) formula.

## Permeability to Water

Permeability or, more importantly, penetrability is the principal factor influencing durability of concrete. The water penetrability of the concrete was determined by an equipment manufactured to German Code DIN 1048. The depth of water penetration monitored on concrete slabs is included in Table 3. The results suggest that the water penetration, and hence the durability, is much more sensitive to lack of curing than is compressive strength. As the water-curing of slabs was reduced from 28 to 7, 3, and 1 days, the depth of water penetration increased by 37, 49, and 84%, respectively. The water penetration in the slabs exposed to the seaside after 1, 3, and 7 days of initial curing is of special importance (Table 3). Whilst the compressive strength of the cubes exposed at the seaside was invariably higher than those which were continously cured, the depth of water penetration increased considerably. In fact, the depth of water penetration of the slabs exposed at seaside was higher than those stored on the rooftop. Perhaps the tropical conditions existing at seaside (concomitant high temperature and humidity) accelerated the rate of hydration and hence led to less uniform pore structure. Whilst this resulted in a higher strength at 28 days, it developed a more easily penetrable pore structure. These results establish the need for initial curing of coastal structures where durability of concrete is of paramount importance. The results also suggest that strength and durability are not always synonymous.

As there was no data available on the water penetrability of normal weight concrete using this test, additional slabs of differing strength grade predominantly used in Kuwait were also cast and tested. The results are included in Table 4. As shown in Table 4, the water penetrability of the SLWC is comparable to the NWC of similar strength grade. The results also suggest greater permeability of the site-mixed concrete, which is commonly used in Kuwait housing developments.

### Drying Shrinkage

Six 50 × 50 × 285 mm shrinkage prisms were cured in a water tank maintained at 23 ± 2°C for 6 days after demolding. The prisms were then removed from the water tank, surface moisture was wiped off, and the zero reading was taken using screws embedded in the specimens and a length comparator. The specimens were stored in a control room maintained at a temperature of 23 ± 1°C and a RH of 50 ± 4%. The length change was then monitored after 1, 3, 7, 14, 28, and 91 days. The procedure adopted is similar to ASTM Standard (20).

Drying shrinkage strain shown in Figure 1 is the average for six specimens. The shrinkage strain of 640 microstrain at the age of 3 months is moderately high. However, Nilsen and Aitcin (19) have reported shrinkage of 156 microstrain at the age of 128 days after 7 days of initial water curing for a SLWC of 91 MPa 28-day compressive strength made with expanded shale as coarse aggregate and natural sand. Likewise, Kayyali and Haque (8) have reported a low shrinkage value up to an age of 91 days of approximately

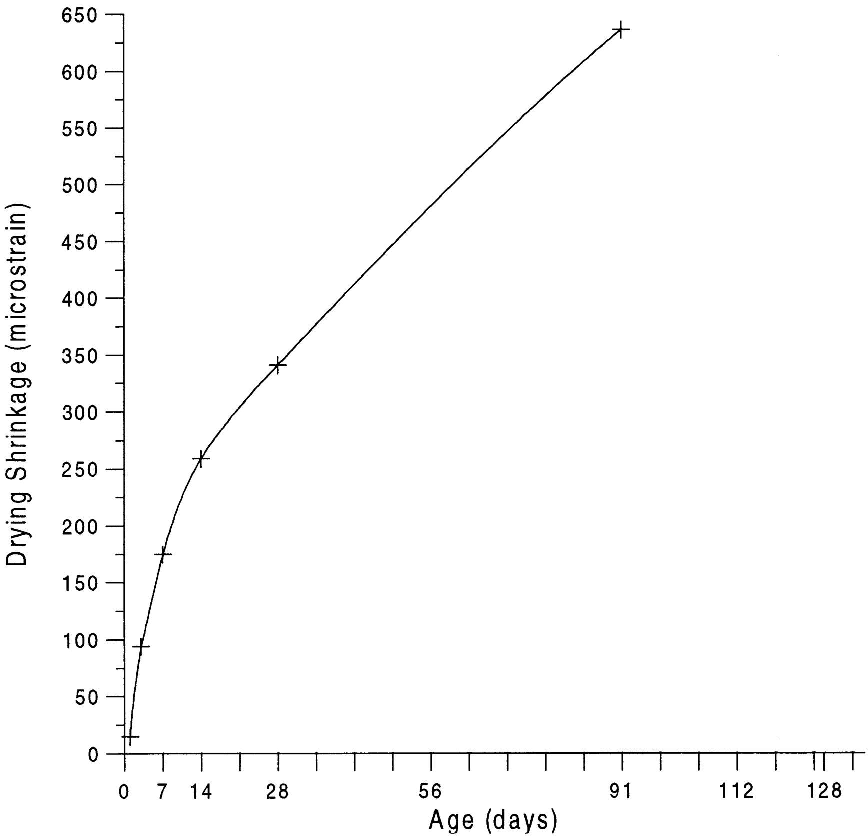


FIG. 1.
Drying shrinkage of SLWC.

450 microstrain for a SLWC of somewhat similar proportions as reported here. The long-term shrinkage of the concrete is being monitored which will enable to explain the mechanism of drying shrinkage of the lightweight concrete.

## Conclusions

1. The compressive strength of SLWC seems to be less sensitive to lack of curing than the NWC, at least in the first month of exposure. This is attributed to the “inner water” stored in the porous aggregate of the SLWC. However, lack of curing seems to affect long-term strength development of SLWC in a similar way as it does the NWC.
2. The depth of water penetration, which is indicative of permeability, was found to be much more sensitive to the extent of initial curing of SLWC. Whilst the compressive strength of specimens exposed to seaside ambient conditions was higher than those continuously stored in water, their water penetrability almost doubled when initial curing was 1 day. These results indicate the importance of initial curing of coastal structures.
3. The drying shrinkage of the SLWC upto a period of 3 months was more than 600 microstrain. Further long-term strain measurement is being monitored in order to be more conclusive.

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