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# Long-term strength development of concrete in arid conditions

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**Abstract**

A long-term investigation into the development of the compressive strength of various concretes, subjected to Kuwait hot and arid environmental conditions is reported. The main parameters investigated included, w/c ratio, cement type and content, and admixture type and its dosage. Other parameters investigated included the effects of using different water curing periods, curing compounds, and casting season. Forty-seven different mixes were placed on the roof of the laboratory building and were exposed to the environment. Compression tests on 100 mm cubes were carried out over a period in excess of five years.

The results generally showed that the compressive strength of the concrete increased with age. The gain in strength at 1800 days above that at 28 days varied considerably depending on the concrete constituents and curing procedure. Concretes made with white Portland cement achieved higher compressive strengths than those made with ordinary or sulphate resisting Portland cements. Also, the type and dosage of admixture influenced the compressive strength of concrete. An increase in the water-curing period was more effective in improving the 28-day compressive strength than the 1800-day strength. The use of curing compounds or silica fume appeared to influence the early age strength more than the long-term strength. Compression test results from selected mixes at the age of 10 years indicated that there was little or no increase in strength during the previous five years. 

*Keywords:* Admixtures; Cement; Compressive strength; Concrete; Curing compounds; Fly ash; Silica fume; Environment; Water/cement ratio; Water curing

## 1. Introduction

The strength of concrete is traditionally characterized by the 28-day value. However, strength of concrete is expected to increase with time at a continuously diminishing rate. Knowledge of the strength-time relationship is of importance when a structure is subjected to a certain type of loading at a later age [12]. Many factors can significantly influence the compressive strength of concrete. These include cement type, w/c ratio, aggregate content, water curing period, and exposure conditions. Water/cement ratio affects the rate of gain in strength and it has been reported that as mixes with low w/c ratios gain strength more rapidly than mixes with higher w/c ratios [11]. Washa and Wendt [15] presented results for concrete made with high early strength Portland cement where the strength at 50 years was 2.4 times the 28-day strength. Another study by Walz [14] showed that the 30-year strength of ordinary Portland cement (OPC) concrete was 2.3 times the 28-day strength while that of Portland blast furnace slag cement concrete was 3.1 times the 28-day strength. Washa and Wendt [15] have also reported that concretes reach their peak strength between 10 and 25 years and thereafter undergo some retrogression of strength while Lange [10] showed that air-cured concretes had about 35% higher strength at three years than that at 28 days.

An earlier study by Gonnerman and Lerch [9] using a concrete mix with a w/c ratio of 0.49 reported that OPC concrete resulted in a gain in strength of 27.5% (over the 28-day strength) in 5 years, while the sulphate resisting Portland cement concrete had a lower 28-day strength, and the gain in strength was 56% over the same period. The compressive strength of concrete made with sulphate resisting cement was about 75–90% of the strength of concrete made with ordinary Portland cement after five years.

Soroka and Baum [13] showed that continuously wet specimens increased 20% in strength above those of the

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the uncured specimens, over 90 days. Also, the 28-day strength of concrete cubes subjected to continuously wet curing was about 40% more than the strength of the corresponding uncured cubes.

Carette et al. [3] reported compressive strength results for a period up to 2 years. Non-silica-fume concretes exhibited an ascending compressive strength during the testing period, while the silica-fume concretes exhibited a plateau or a small decrease in the compressive strength after one year. Aitcin [1] presented results on seven field concretes exposed for periods ranging from 4 to 6 years. Non-silica-fume concretes showed more gain in strength (23–40% in 2 years and 50% in 6 years) than silica-fume concretes (−12% to +29% in 2 years and −31% to +17% in 6 years). Also, in contrast to OPC concrete, which develops the bulk of its ultimate strength by 28 days, the strength development of concrete containing pulverized fuel ash (PFA) not only continues for much longer but varies both with the PFA used and age [4]. Proper curing is more important to the compressive strength development of PFA concrete.

Long-term investigations on the effects of natural environmental conditions of the middle east on concrete properties, in particular the compressive strength are rare. However, a long-term investigation (up to 1300 days) was reported by Fattuhi [5] earlier. The results showed that at early ages the compressive strength of concrete continuously cured in a humidity chamber was slightly lower than that of similar concrete cured under atmospheric conditions. However, this situation was reversed when the concrete cubes were exoposed for more than 1200 days. This highlights the importance of conducting long-term tests. Nevertheless, the above work indicated that the compressive strength of concrete subjected to middle east weather conditions continued to increase with time. Concrete strengths can also be significantly influenced by other factors such as carbonation [7], and in turn, the rate of carbonation is also influenced by mix constituents and the curing regime [6,8].

In this study various parameters affecting the compressive strength are presented. Short- and long-term gains in strength are discussed. Concrete cubes with various constituents were made, and their strengths were measured up to an age of 1800 days while subjected to the arid environmental conditions of Kuwait. The weather in Kuwait is characterized by hot dry periods and the summers usually extend over several months (Fig. 1). Winters are mild with low amounts of rain fall.

## 2. Materials and specimens

The majority of the specimens were made with OPC. White and sulphate resisting cements were also used. Typical fineness for the ordinary, white and sulphate resisting Portland cements used were 349, 392 and 349 $m^2/kg$. The fine and coarse aggregates (see Table 1) consisted of natural desert sand and crushed desert limestone gravel. Twelve admixtures were used in various mixes. Table 2 presents composition and recommended dosages of these admixtures.

Forty-seven concrete mixes were made and the relative proportions of some of their constituents are shown in Table 3. When a liquid-based admixture was added, no adjustment to the water content of the mix was made. Mixes A, M and T were prepared during the preliminary investigations, and were made without using an admixture. The mixes were designed to study the effect of water curing period on concrete compressive strength. Mixes A1 and A2 were prepared first, and the hardened specimens made were found to contain a large amount of surface blowholes. Hence, mixes M1 and M2 were made with increased cement contents, but the surface appearance of the specimens had improved little when compared to mixes A1 and A2. Further modifications

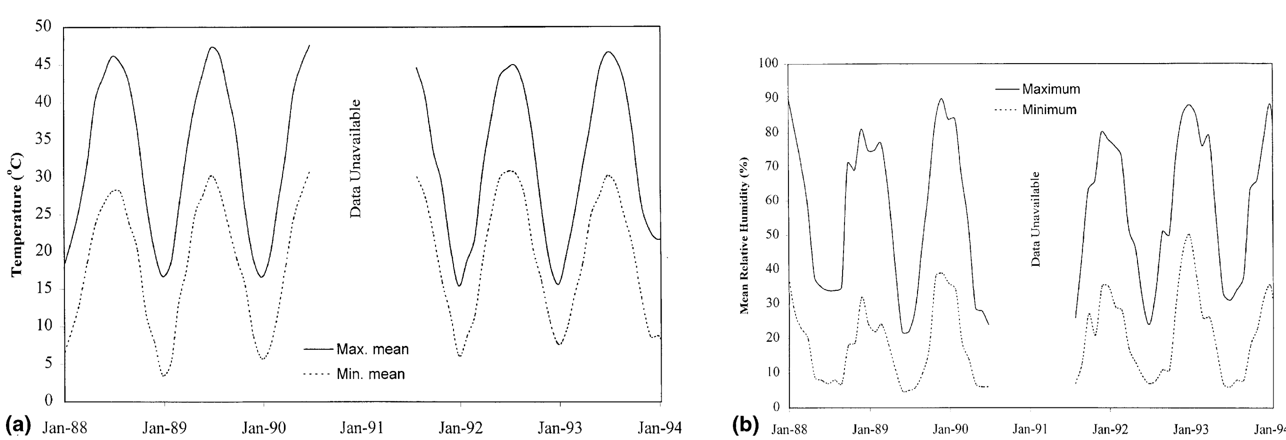


Fig. 1. Weather information.

Table 1
Typical properties of fine and coarse aggregates

| Sieve size (mm) | Cumulative amount passing (%) | |
|---|---|---|
| | Fine aggregate | Coarse aggregate |
| 12.7 | – | 100 |
| 9.52 | – | 92 |
| 4.76 | 100 | 12 |
| 2.38 | 96 | 1 |
| 1.19 | 87 | – |
| 0.6 | 66 | – |
| 0.3 | 24 | – |
| 0.15 | 4 | – |
| Bulk specific gravity | 2.63 | 2.56 |
| Absorption (%) | 1.53 | 1.20 |
| Dry rodded unit weight ($kg/m^3$) | – | 1560 |
| Fineness modulus | 2.20 | – |

were made resulting in concrete mix T (slump = 0 mm), where the total content of the finer solid materials (cement and sand) was increased. However, only a slight improvement in surface appearance of specimens was achieved. A w/c ratio of 0.5 was selected as it is commonly used in Kuwait. Higher w/c ratio generally results in less durable concrete.

Mixes X1 to X6 were designed to study the influence of admixture dosage on the compressive strength. Two superplasticizing admixtures with different chemical compositions were used. In the latter part of the investigations, admixture $\bar{A}_2$ was favoured over admixture $\bar{A}_1$ because of workability and surface finish considerations. A dosage of 1.0% by weight of cement for admixture $\bar{A}_2$ was found to be adequate for obtaining acceptable workability (i.e. 20–50 mm slump) and surface finish. The actual slump test results for mixes X1 to X5 varied between 10 and 48 mm.

Mixes N1 to N5 were designed to study the influence of water curing period. The object of the study was similar to that for mixes T1 to T5, but mixes N1 to N5 contained a smaller quantity of cement due to the presence of a superplasticizing admixture (slump varied between 35 and 39 mm).

Mixes C1 to C3 were designed to study the influence of using different curing compounds/aids on concrete properties. Three curing compounds with different compositions were used and their rate of application were within the manufacturers' recommendation. The results of mixes C1 to C3 will be compared to those for mixes N1 to N5.

Mixes S1 to S9 were designed to study the influence of using different admixtures on concrete properties. The dosages of the nine admixtures used were within the limits recommended by the manufacturers.

Mixes E, E1 to E3 and K contained different amounts of cement and their w/c ratios were varied between 0.45 and 0.80. Initially, it was intended to start with as low w/c ratio as possible. Therefore, many mixes were designed and made to achieve a w/c ratio of 0.40, but it was found that in order to obtain an acceptable workability and surface finish, the mix must contain either a large dose of admixture $\bar{A}_2$ or a higher

Table 2
Properties of admixtures

| Admixture | Composition | Dosage[a] by weight of cement (%) |
|---|---|---|
| $\bar{A}_1$ | High range water-reducer based on soluble salt of a polymeric sulfonate, no chloride content, origin – UK | 0.5–1.0 |
| $\bar{A}_2$ | High range water-reducer based on modified condensation product of melamine and formaldehyde, no choride content, powder/water ratio = 1/4 by weight, origin – Germany | 1.5–5.0 |
| $\bar{A}_3$ | Water-reducer and retarder based on ligno-sulfonates, no chloride content, origin – UK | 0.25–0.50 |
| $\bar{A}_4$ | Water-reducer and retarder based on Lignin, no chloride content, origin – UK | 0.3–1.0 |
| $\bar{A}_5$ | A special admixture to improve concrete properties based on an amalgam of 22 different chemicals, origin – UK | 3.0 |
| $\bar{A}_6$ | Retarder based on phosphate, chloride content = 0.01%, powder/water ratio = 1/3 by weight, origin – Germany | 1.0–20.0 |
| $\bar{A}_7$ | Plasticizer based on calcium lignosulfonate, no chloride content, origin – Kuwait | 2.6 |
| $\bar{A}_8$ | Water-reducer and retarder based on calcium lignosulfonate, no chloride content, origin – Kuwait | 2.6 |
| $\bar{A}_9$ | High range water-reducer based on condensate of sodium naphthalene sulfonate with formaldehyde no chloride content, origin – Kuwait | 7.6–13.0 |
| $\bar{A}_{10}$ | High range water-reducer and retarder based on condensate of sodium naphthalene sulfonate with formaldehyde, no chloride content, origin – Kuwait | 7.6–13.0 |
| $\bar{B}_1$ | Silica fume in dry powder form, origin – Norway | 10 |
| $\bar{B}_2$ | Pulverized fuel ash, origin – UK | 10–20 |

[a] Manufacturer recommended dosage (except for the supplementary cementitious materials; $\bar{B}_1$ and $\bar{B}_2$).

Table 3
Concrete mixes

| Mix | Water/cement ratio[a] | Cement content (kg/m$^3$) | Duration of Laboratory curing before outside exposure (days) | | Admixture | |
|---|---|---|---|---|---|---|
| | | | Water | Laboratory air | Type | Dosage by weight of cement (%) |
| A1 | 0.500 | 435 | 6 | 21 | – | – |
| A2 | 0.500 | 435 | 27 | – | – | – |
| M1 | 0.500 | 460 | 6 | 21 | – | – |
| M2 | 0.500 | 460 | 27 | – | – | – |
| X1 | 0.500 | 410 | 6 | 21 | $\bar{A}_1$ | 0.30 |
| X2 | 0.500 | 410 | 6 | 21 | $\bar{A}_1$ | 0.50 |
| X3 | 0.500 | 410 | 6 | 21 | $\bar{A}_2$ | 1.00 |
| X4 | 0.500 | 410 | 6 | 21 | $\bar{A}_2$ | 0.85 |
| X5 | 0.500 | 410 | 6 | 21 | $\bar{A}_2$ | 2.00 |
| X6 | 0.500 | 410 | 6 | 21 | $\bar{A}_2$ | 0.50 |
| N1 | 0.500 | 410 | 27 | – | $\bar{A}_2$ | 1.00 |
| N2 | 0.500 | 410 | 13 | 14 | $\bar{A}_2$ | 1.00 |
| N3 | 0.500 | 410 | 6 | 21 | $\bar{A}_2$ | 1.00 |
| N4 | 0.500 | 410 | 2 | 25 | $\bar{A}_2$ | 1.00 |
| N5 | 0.500 | 410 | – | 27 | $\bar{A}_2$ | 1.00 |
| C1 | 0.500 | 410 | – | 27 | $\bar{A}_2$ | 1.00 |
| C2 | 0.500 | 410 | – | 27 | $\bar{A}_2$ | 1.00 |
| C3 | 0.500 | 410 | – | 27 | $\bar{A}_2$ | 1.00 |
| S1 | 0.500 | 410 | 6 | 21 | $\bar{A}_3$ | 5.0 ml/kg |
| S2 | 0.500 | 410 | 6 | 21 | $\bar{A}_4$ | 0.68 |
| S3 | 0.500 | 410 | 6 | 21 | $\bar{A}_2$ | 3.00 |
| S4 | 0.500 | 410 | 6 | 21 | $\bar{A}_5$ | 3.00 |
| S5 | 0.500 | 410 | 6 | 21 | $\bar{A}_6$ | 0.60 |
| S6 | 0.500 | 410 | 6 | 21 | $\bar{A}_7$ | 2.6 ml/kg |
| S7 | 0.500 | 410 | 6 | 21 | $\bar{A}_8$ | 2.6 ml/kg |
| S8 | 0.500 | 410 | 6 | 21 | $\bar{A}_9$ | 13.0 ml/kg |
| S9 | 0.500 | 410 | 6 | 21 | $\bar{A}_{10}$ | 13.0 ml/kg |
| T1 | 0.500 | 460 | – | 27 | – | – |
| T2 | 0.500 | 460 | 13 | 14 | – | – |
| T3 | 0.500 | 460 | 27 | – | – | – |
| T4 | 0.500 | 460 | 2 | 25 | – | – |
| T5 | 0.500 | 460 | 6 | 21 | – | – |
| R[b] | 0.500 | 410 | 6 | 21 | $\bar{A}_2$ | 1.00 |
| W[c] | 0.500 | 410 | 6 | 21 | $\bar{A}_2$ | 1.00 |
| E | 0.500 | 410 | 6 | 21 | $\bar{A}_2$ | 1.00 |
| E1 | 0.600 | 342 | 6 | 21 | $\bar{A}_2$ | 1.00 |
| E2 | 0.700 | 293 | 6 | 21 | $\bar{A}_2$ | 1.00 |
| E3 | 0.800 | 256 | 6 | 21 | $\bar{A}_2$ | 1.00 |
| K | 0.450 | 456 | 6 | 21 | $\bar{A}_2$ | 1.00 |
| P | 0.500 | 410 | 6 | 21 | $\bar{A}_2$ | 1.00 |
| Q | 0.600 | 342 | 6 | 21 | $\bar{A}_2$ | 1.00 |
| V | 0.700 | 293 | 6 | 21 | $\bar{A}_2$ | 1.00 |
| Z | 0.800 | 256 | 6 | 21 | $\bar{A}_2$ | 1.00 |
| O | 0.450 | 456 | 6 | 21 | $\bar{A}_2$ | 1.00 |
| H | 0.556 | 369 | 6 | 21 | $\bar{A}_2$ | 1.00 |
| | | | | | $\bar{B}_1$ | 11.11[d] |
| H2 | 0.625 | 328 | 6 | 21 | $\bar{A}_2$ | 1.00 |
| | | | | | $\bar{B}_1$ | 25.00[e] |
| H3 | 0.556 | 369 | 6 | 21 | $\bar{A}_2$ | 1.00 |
| | | | | | $\bar{B}_2$ | 11.11[d] |
| H4 | 0.500 | 410 | 6 | 21 | $\bar{A}_2$ | 1.00 |
| | | | | | $\bar{B}_1$ | 10.00 |

| Mix | Water/cement ratio[a] | Cement content ($kg/m^3$) | Duration of Laboratory curing before outside exposure (days) | | Admixture | |
|---|---|---|---|---|---|---|
| | | | Water | Laboratory air | Type | Dosage by weight of cement (%) |
| H5 | 0.500 | 410 | 6 | 21 | $\bar{A}_2$ | 1.00 |
| | | | | | $\bar{B}_2$ | 10.00 |
| H6 | 0.500 | 410 | 6 | 21 | $\bar{A}_2$ | 1.00 |

[a] Additional water from admixtures not included, and ratio is by weight of cement only.
[b] Contains sulphate resisting Portland cement.
[c] Contains white Portland cement.
[d] Or 10% by weight of cement in mix H6.
[e] Or 20% by weight of cement in mix H6.

amount of cement. Hence, a compromise w/c ratio of 0.45 was used.

Mix R contained a sulphate resisting Portland cement, while mix W contained an ordinary white Portland cement. Their results are compared with those for mix E.

Mixes O, P, Q, V and Z are a repeat of mixes, K, E, and E1 to E3 which were designed to study the effect of w/c ratio on concrete compressive strength. The former mixes were cast during the winter season while the latter ones were cast during the summer season.

Mixes H1 to H6 were designed to study the effects of the addition of silica fume or pulverized fuel ash (PFA) on the compressive strength of concrete. Basically, mix H6 (similar to mix X3, see Table 3) was used and modified to include the silica fume or PFA admixtures. In mixes H1 and H2, silica fume was used to replace OPC by 10% and 20% by weight, respectively. Also, in mix H3, PFA was used to replace 10% of OPC by weight, while in mix H4, silica fume was used to replace 10% of the sand (by weight). In mix H5, PFA was used to replace 10% of the sand, by weight. Note that all these percentages are relative to the original quantities of OPC and sand used in mix H6. The cement content for concrete H2 was 329 $kg/m^3$, while that for concrete H1 and H3 was 369 $kg/m^3$. Concrete H4, H5 and H6 had the highest cement content of 410 $kg/m^3$. The water binder ratio was 0.5 for mixes H1, H2, H3 and H6 while it was 0.45 for mixes H4 and H5.

A horizontal rotating cum-flow type mixer of 0.1 $m^3$ capacity was used for preparing the concrete mixes. The dry materials were first placed inside the laboratory for several hours. Later, they were mixed thoroughly in the mixer. The mixing water, including any admixture, was then added gradually, and mixing was continued until a uniform concrete was achieved, as determined by visual inspection. In general, concrete batches were prepared to make cubes (100 mm) and various size prisms to determine other concrete properties (to be reported elsewhere). Steel moulds were used for making cubes which were compacted on a vibrating table.

The concrete was cast in two layers; then the cubes were covered with polythene sheets until demoulding, 18–24 h later. The air temperature in the laboratory varied between 21°C and 26°C during preparation of specimens, while the temperature of fresh concrete varied between 25°C and 28°C. After demoulding, all specimens were kept inside the laboratory for a further period of 27 days before they were removed and placed on the roof of the laboratory building. During the 27-day period, some specimens were cured in air while others were cured in water (in curing tanks) for different periods.

Cubes C1–C3 were placed in water for a period of 3–4 h immediately after demoulding. They were then removed, hung (form wires embedded in the concrete during casting) and surface dried. The required amount of curing compound for each specimen was prepared earlier, and it was brushed onto each specimen in different directions several times, until all the quantity of curing compound was used up. The procedure for brushing the specimens with the curing compounds lasted between 2 and 3 h.

The compressive strength for the cubes was determined by using a 2000 kN capacity compression testing machine. The specimens were surface dried before testing. All cubes were loaded on their sides following the procedure described in BS 1881 (British Standards 1983) [2]. Each strength result reported included in the tables is an average value of three specimens.

## 3. Test results and discussion

At 28 days of age, the cubes were exposed to the atmospheric conditions of Kuwait by placing them on the roof of the laboratory building. Hence the cubes were subjected to sun radiation, higher and more fluctuating temperatures, and possibly higher concentrations of air pollutants. The sun radiation, and higher and more fluctuating atmospheric temperatures, can affect the concrete in two ways. Aggregate and cement paste have different coefficients of thermal expansion, and the contraction and expansion process that the concrete is subjected to can lead to micro-cracking at the aggregate-cement paste interface, consequently resulting in lower compressive strength. Also, higher temperatures lead to quicker evaporation of free water from hardened concrete, resulting in desiccation (i.e., stoppage of the hydration process). However, higher temperatures can also lead to higher rates of reaction (hydration) provided that there is enough moisture in the concrete, hence, higher strengths. Carbonation can also lead to an increase in the compressive strength of concrete.

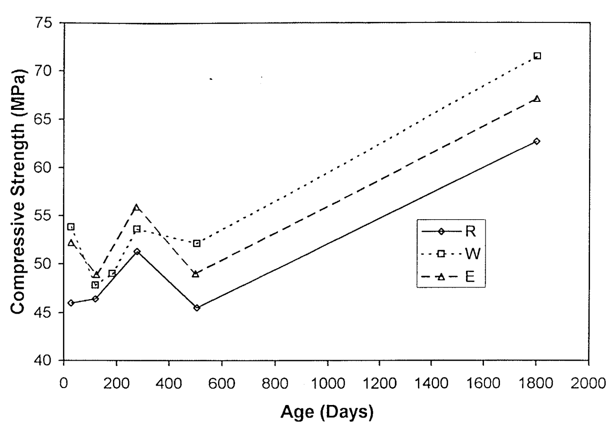


Fig. 2. Compressive strength of concrete containing different cements.

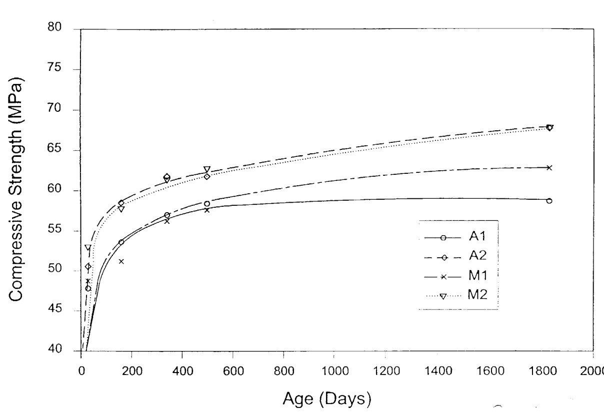


Fig. 3. Compressive strength of concrete containing various cement contents.

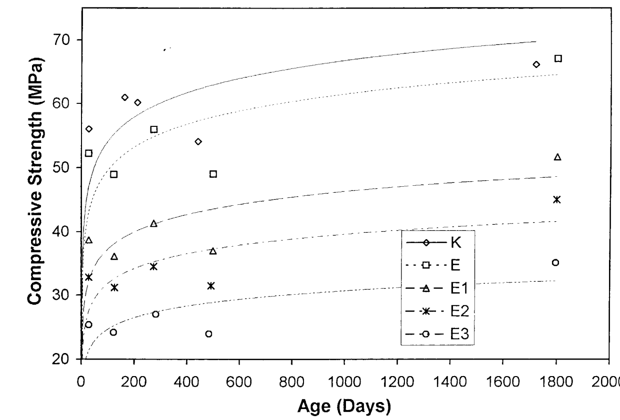


Fig. 4. Compressive strength of concrete with various w/c ratios cast during the summer.

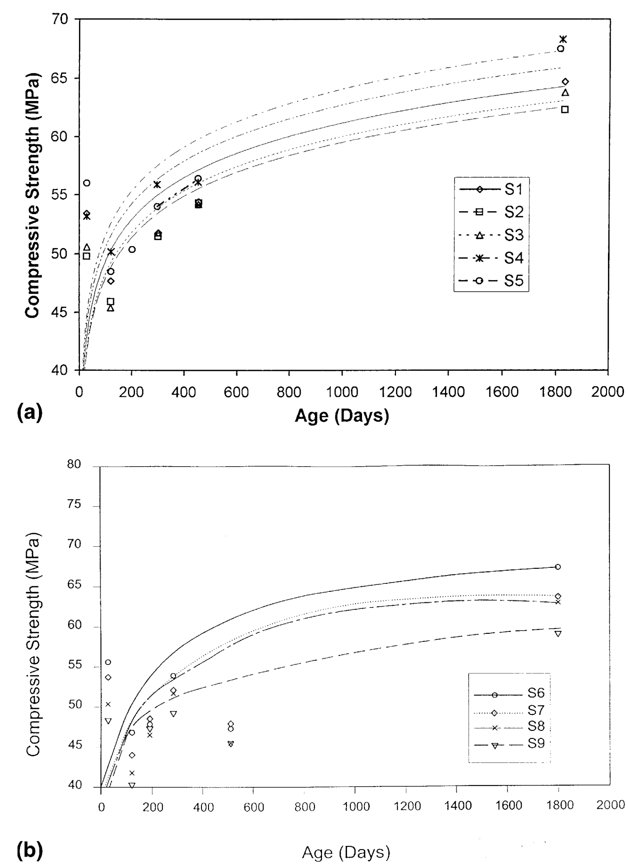


Fig. 5. (a) and (b) Compressive strength of concrete containing different admixtures.

The compressive strength test results for the various concrete mixes are shown in Figs. 2–11. The results generally showed that there was a continuous increase in strength with time for concrete mixes prepared during

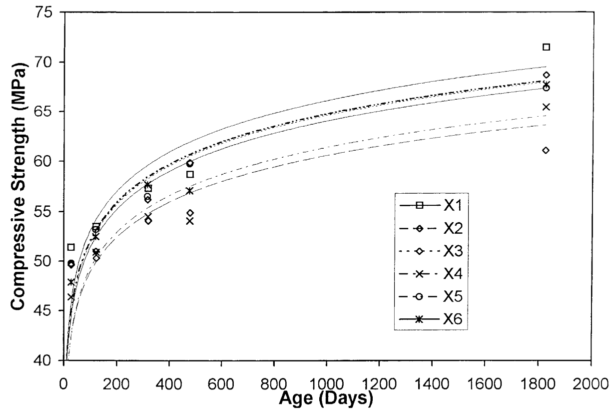


Fig. 6. Compressive strength of concrete containing various dosages of admixture $\bar{A}_1$.

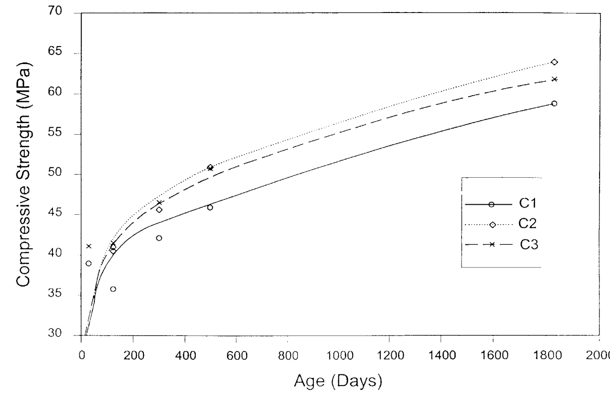


Fig. 9. Compressive strength of concrete brushed with various curing compounds.

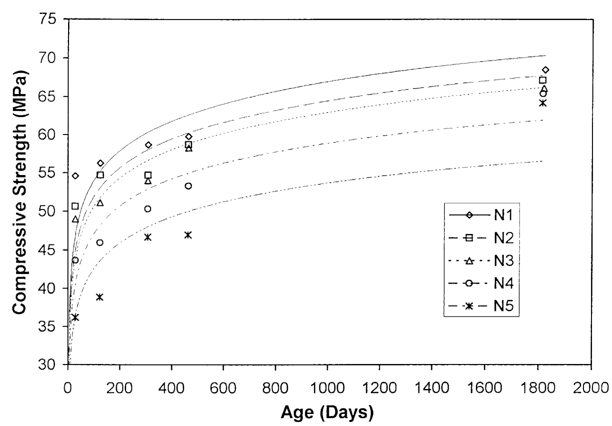


Fig. 7. Compressive strength of concrete containing admixture $\bar{A}_2$ and subjected to various water curing periods.

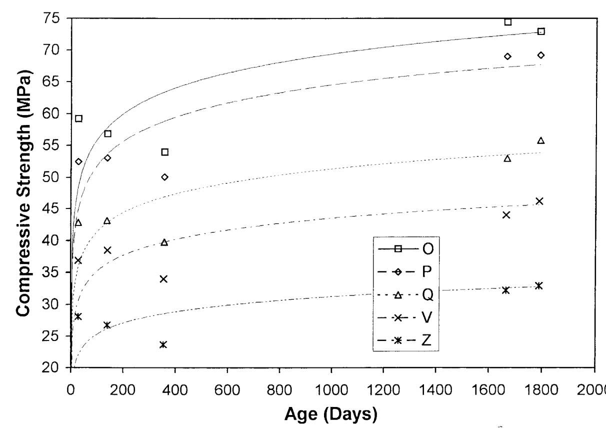


Fig. 10. Compressive strength of concrete with various w/c ratios cast during the winter.

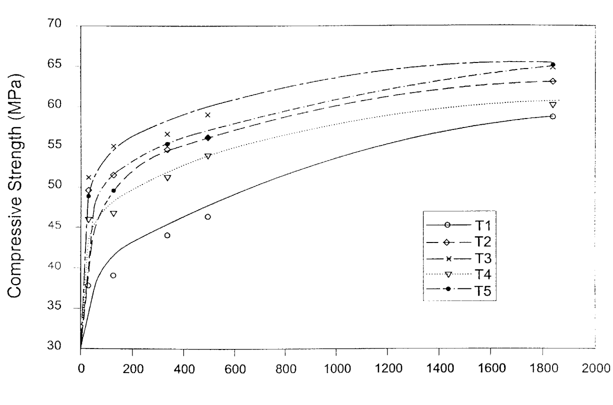


Fig. 8. Compressive strength of concrete subjected to various water curing periods (without admixture $\bar{A}_2$).

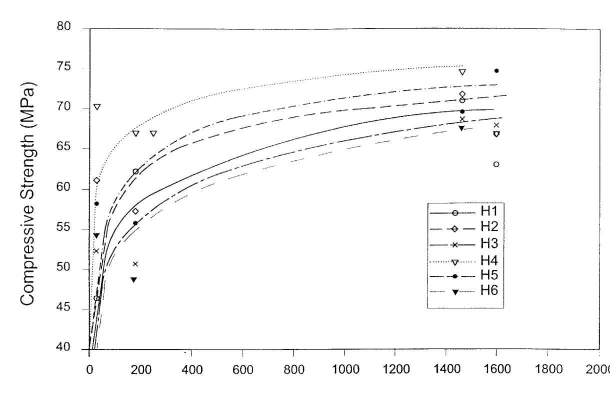


Fig. 11. Compressive strength of concrete containing silica fume or PFA.

the earlier stages of the research programme (mixes A1 to N5 – Table 3). However, for the remaining mixes, the results showed that the level of the compressive strength slightly fluctuated up to the age of 18 months. Testing at 500 days (December for most mixes) produced lower compressive strength than earlier testing. The reasons behind this behaviour are not clear, but it is worth noting that after removing the specimens of the latter mixes from the laboratory, they were suddenly exposed to hotter and drier conditions. Results at the end of the testing programme generally indicated that the compressive strengths of the various concrete mixes appeared to be higher than their equivalents when tested at 28 days. An increase of 77% was noted for mix N5. Also, several mixes exhibited increases in their compressive strengths of more than 40%. However, for mix A1 there was almost no increase in the compressive strength.

## 4. Cement type

Three Portland cements were used: ordinary (mix E), white (mix W) and sulphate-resisting (mix R). The results showed (see Fig. 2) that the 28-days average compressive strength was highest for the white cement concrete (53.8 MPa), followed closely by the OPC concrete (52.2 MPa). However, the sulphate-resisting Portland cement concrete had an average compressive strength value of 46.0 MPa at 28 days. All specimens continued to gain strength with time. Specimens made with white cement had an average compressive strength of 71.5 MPa at 1800 days showing an increase in strength of 33% when compared to the 28-day strength. The compressive strength of OPC concrete was 67.1 MPa at 1800 days showing an increase of 29%, while the average strength for the sulphate resisting cement concrete was 62.7 MPa (an increase of 36%). This is possibly because the latter contained a higher proportion of dicalcium silicate compound, which normally reacts at a slower rate with time.

The average gain in strength above the 28-day values over 1800 days was 33%. It should be noted that the compressive strength measurements were taken during the winter period, and that the average carbonation depth for these specimens was less than 6 mm.

## 5. Cement and aggregate contents

Mix A had a cement content of 435 kg/m$^3$, while mix M had a cement content of 460 kg/m$^3$ (see Table 3). Concrete specimens A1 and M1 were water cured for 6 days while specimens A2 and M2 were water cured for 27 days after demoulding.

Fig. 3 shows the compressive strength results for the four sets of concrete specimens A and M. It can be seen that by increasing the water curing period from 6 to 27 days, higher compressive strengths were obtained at all ages. The differences in the compressive strengths were between 6% and 15% for both concretes (A and M) throughout the exposure period.

The gain in the compressive strength over 1800 days compared to the strength at 28 days ranged between 23% and 34%. Concrete A1 exhibited the lowest gain in strength while concrete A2 had the highest gain in strength.

Comparing concretes water cured for the same period, showed that by increasing the cement content from 435 to 460 kg/m$^3$ (thus decreasing aggregate content) little advantage in the compressive strength was gained. The maximum change in strength was about 7% for concrete water cured for 6 days and 5% for concrete water cured for 27 days.

## 6. Water/cement ratio

The w/c ratios for concretes K, E, E1, E2 and E3 ranged from 0.45 to 0.80. The results (Fig. 4) showed that as the w/c ratio increased there was a significant decrease in the compressive strength. The 28-day compressive strength for the concrete with a w/c ratio of 0.45 (mix K) was 56.0 MPa, while that for concrete with a w/c ratio of 0.60 (mix E1) was only 38.7 MPa. Although concretes with w/c = 0.6 and above have not been recommended in Kuwait since the eighties, such concretes have been used in the past. Also, in private construction, concretes with high w/c ratios are still possibly used, since admixtures are thought to be an expensive addition.

Fig. 4 shows that there was little gain in strength over the first 18 months. However, at later ages, all concretes continued to gain strength with time. At about 1800 days, the gain in strength above the 28-day value was 18% for the concrete with a w/c ratio of 0.45 (mix K). However, the gain in strength for the other w/c ratios exceeded 29%. The highest gain in strength of 38% was that for concrete with a w/c ratio of 0.80 (mix E3). It is worth noting that by increasing the w/c ratio, the rate of concrete carbonation is also increased, and consequently, the concrete becomes more dense. This may partially explain why there were higher gains in strengths for concretes with high w/c ratios [6,7].

## 7. Type and dosage of admixture

Various types of admixtures were used to make concrete mixes S1–S9 and the workabilities of these mixes as measured by the slump test, varied between 8 and 70 mm. The maximum difference in the compressive strength at 28 and 1800 days for the various admixtures was about 16% (see Fig. 5). The gain in strength at 1800 days over the 28-days value ranged from 18% to 28%. The highest compressive strength at 28 days was that for a concrete (mix S5), containing an admixture $\bar{A}_6$ (retarder based on phosphate). Admixture $\bar{A}_{10}$, a high range water-reducer and retarder based on condensate of sodium naphthalene sulphonate with formaldehyde, resulted in concrete (mix S9) with the lowest compressive strength values at 28 and 1800 days. However, the compressive strength of mix S9 could have been increased by reducing the w/c ratio, since the workability of this concrete was high (slump = 70 mm).

The effect of admixture, $\bar{A}_2$ dosage on the compressive strength can be seen when comparing the results of concrete mixes X3 to X6 and S3 (see Figs. 5(a) and 6). The dosage of admixture $\bar{A}_2$ was varied from 0.5% to 3% by weight of cement. Using an admixture dosage of 3% in mix S3 resulted in the highest 28-day compressive strength. The gain in strength up to an age of 1830 days was 26%. However, when using a lower dosage of admixture $\bar{A}_2$ (i.e., 0.5% for mix X6 and 0.85% for mix X4), the gain in strength for these mixes up to an age of 1823 days was 41%. Also, the 1823-day compressive strengths for these mixes were higher than that for mix S3 (i.e. dosage 3%).

Two dosages (0.3% and 0.5%) of admixture $\bar{A}_1$ were also used. Concrete specimens X1 containing the lower dosage of admixture $\bar{A}_1$ exhibited higher compressive strengths up to a period of 1823 days. This could have been partially due to the fact that an increase dosage of the admixture resulted in a slight increase in the w/c ratio, and thereby lowering the compressive strength.

Cubes of two different sizes were sawn off concrete prisms from three selected mixes and were tested at ages between 3651 and 3665 days. The results showed that the compressive strength of specimen S1 (100 mm cube) was 63.9 MPa, while those for specimens S8 and S9 (75 mm cubes) were 60.6 and 57.3 MPa, respectively, These results indicate that for these mixes, there was little change in strength during the period from 5 to 10 years.

## 8. Water-curing period

Concrete specimens N1–N5 were water cured for periods ranging from 0 to 27 days. These specimens contained admixture $\bar{A}_2$. At 28 days, increasing the water-curing period from 0 (mix N5) to 27 days (mix N1) resulted in an increase of 51% in the compressive strength (see Fig. 7). However, this difference in strength was almost halved by initially water curing for 2 days only. At 1800 days, the advantage of increasing the water curing period from 0 to 27 days was only about 7%. This clearly indicated that despite the fact that concrete specimens N5 were initially air-cured only, the compressive strength continued to increase while exposed to natural atmospheric weather up to the age of 1814 days. The maximum gain in strength measured over the 28-day strength was about 77%. The reason behind this are not clear, but the higher carbonation of specimens N5 (8.5 mm) when compared to specimens N1 (5.4 mm) must have had a contributory effect towards this gain in strength.

Concrete specimens T were similar to N, but the former did not contain an admixture. Figs. 7 and 8 show that the compressive strength of concrete specimens N and T were nearly similar up to an age of 500 days. However, at an age of more than 1800 days, concrete specimens N water cured for either 0, 2, 13 or 27 days, exhibited higher compressive strengths than concrete specimens T. It is not clear why the long-term strengths of concrete specimens N were generally higher than those for specimens T since the former contained less cement content. One possible reason is that concrete specimens N achieved better compaction since they contained a superplasticizing admixture, and consequently with the passage of time, led to the formation of a better quality cement gel in the hardened concrete.

It should be noted that for concrete specimens N and T, increasing the water curing period from 6 to 13 days did not appear to produce any advantage in respect of the compressive strength of concrete. Therefore, for economic and practical purposes, it is recommended that the water curing period of 6 days is quite adequate. However, it should be noted that this may result in a small increase in concrete carbonation.

Cubes of two different sizes were sawn off concrete prisms from three selected mixes and were tested at ages between 3700 and 3707 days. The results showed that the compressive strength of specimen T1 and T5 (100 mm cube) were 53.5 and 68.4 MPa, respectively, while that for specimen T2 (75 mm cubes) was 69.8 MPa. These results indicate that for these mixes, there was little change in strength during the period from 5 to 10 years.

## 9. Curing compounds

Three curing compounds/aids were used; $\bar{C}_1$ based on sodium silicate, $\bar{C}_2$ based on resin and $\bar{C}_3$ based on wax emulsion. These compounds were used in concrete specimens C1, C2 and C3, respectively. Specimens C2 and C3 showed slightly higher compressive strengths than specimens C1 (see Fig. 9). However, the maximum difference between the compressive strengths of the concretes brushed with either one of the three curing compounds throughout the testing period was about 9%.

Figs. 7 and 9 show that the compressive strength of concrete specimens brushed with the various curing compounds at the age of 28 days were slightly higher than specimens N5 (air-cured). However, at an age of more than 1800 days, only concrete specimens C2 had as high a compressive strength as specimens N5. This indicated that there was no long-term benefit (in respect of compressive strength) from using curing compounds. This is thought to be due to the continued hydration of the cement compounds and the carbonation of mix N5, as explained earlier.

## 10. Casting weather conditions

Concrete specimens K, E, E1, E2 and E3 were cast during the summer. However, concrete specimens O, P, Q, V and Z were similar but were cast during the winter period. These specimens had w/c ratios ranging from 0.45 to 0.80.

Results of concrete specimens cast during the winter period (see Fig. 10) show similar trends to those cast during the summer. As the w/c ratio was increased, the compressive strength decreased as expected. However, the compressive strengths were higher for concrete specimens cast during the winter than those cast during summer period. The differences in the strengths of the specimens were larger when the w/c ratio was decreased. The long-term gain in strength over the 28-day strength for specimens cast during the winter period ranged from 17% to 32% with an average of 26% compared with 18–38% with an average of 31%, for specimens cast during the summer period.

## 11. Silica fume or PFA

Fig. 11 shows the compressive strength results for concrete specimens H1–H6. The water binder ratio (w/b) for mixes H4 and H5 was 0.45 and for the other mixes it was 0.5. At 28 days, concrete specimens H4 which had silica fume replacing 10% of sand by weight and with a cement content of 410 kg/m$^3$, achieved the highest compressive strength of 70.3 MPa, followed by concrete specimens H2 at 61.1 MPa which contained more silica fume and less cement. Concrete specimens H4, H5 and H6 had a similar w/c ratio and cement content. However, the w/b ratio for mix H6 was higher. The concrete specimens containing silica fume (H4) exhibited the highest compressive strength at 28 days followed by specimens containing PFA (H5), while specimens without silica fume or PFA (H6) had the lowest compressive strength. The results clearly demonstrate that the addition of silica fume was more effective in increasing the compressive strength than the addition of pulverized fuel ash (PFA). This was particularly true at early ages. However, after long-term exposure, the differences in strengths appeared to reduce and could possibly diminish, further testing is required to verify this.

## 12. Conclusions

1. Concretes made with white Portland cement showed the highest compressive strength values, followed by ordinary Portland cement and sulphate resisting Portland cement. The average gain in strength (above the 28-day values) over 1800 days for the three types of concrete was 33% (ranged from 29% to 36%).
2. The compressive strength of the concrete decreased significantly as the w/c ratio increased as expected. The higher the w/c ratio, the higher was the gain in strength with age above the 28-day value. In the case of concrete with w/c ratio of 0.60, the gain in strength was 34%.
3. The compressive strength appeared to vary slightly (maximum 16%) when different types of chemical admixtures were used. The gain in strength at 1800 days over that at 28 days for mixes containing a lower dosage (below 0.85%) of admixture $\bar{A}_2$ was higher (up to 41%) than those for mixes containing higher admixture dosages (a gain of 26% for a dosage of 3%).
4. At 28 days, increasing the water curing period from 0 to 27 days resulted in an increase of 51% in the compressive strength. This difference in strength was almost halved by initially water curing for 2 days only. However, at 1800 days, the advantage of increasing the water curing period from 0 to 27 days was only about 7%. The results also indicated that there was only a nominal increase in compressive strength of concrete by extending the water curing beyond 6 days. However, longer curing may be beneficial from the durability point of view.
5. The results indicated that the compressive strength of concretes brushed with curing compounds were slightly higher than that for air-cured concrete. However, there was no long-term benefit in terms of the compressive strength from using curing compounds.
6. The compressive strengths were higher for concrete specimens cast during the winter than those cast during the summer. However, the average long-term gain in strength over the 28-day strength for specimens cast during the winter was lower than that for specimens cast during the summer.
7. At early ages, the addition of silica fume to concrete was more effective in increasing the compressive strength than the addition of PFA. However, after 5 years, the difference in strength was marginal.

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