

The compressive strength of a new ureaformaldehyde-based polymer concrete

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Standard test specimens of ureaformaldehyde-based polymer concrete (PC) prepared with various amounts of ureaformaldehyde (UF) resin and cured at temperatures in the range 90 to 150°C for periods up to 21 d were tested in compression. The PC having a resin content of 8% and cured at 110°C for about 7 d, developed an ultimate compressive strength of 37 MPa. The strength values of PC specimens are compared with those of Portland cement concrete (PCC) specimens prepared with different water/cement ratios and mix proportions. For certain mixes the compressive strength of PCC is surpassed by that of PC having a similar binder content and comparable workability.

1. Introduction

The potential utilization of polymers in building materials has received wide attention [1]. Polymer concrete (PC), using a wide range of monomers and resins, has been found to be suitable for lightweight engineering materials [2], highway and structure-related applications [3], agricultural buildings [4], geotechnical engineering, and precast as well as cast-in-place applications in several countries [5].

In polymer concrete, a thermoplastic or, more commonly, a cross-linked polymer, is used to replace Portland cement as binder in a concrete mix. The behaviour of the composite is determined by the polymer which constitutes the continuous phase and whose properties are dependent on time and temperature.

Early research on PC utilized epoxy, polyester and furan resins [6], while recently methyl methacrylate and styrene monomers have been employed. Although new formulations continue to appear, and mix design has been studied systematically, both scientific and engineering research on PCs has been limited in scope [5] with a notable exception in the development of PCs for geothermal applications [7].

Amino resin of the ureaformaldehyde type is abundantly available in many countries in the world and possesses an outstanding potential for use as an attractive substitute for expensive polymer binders at a considerably reduced cost. Amino resins are the condensation polymerization products of amino compounds with aldehydes. Ureaformaldehyde and melamineformaldehyde are commercially the most important members of the amino group of resinous binders. Of the two resins, ureaformaldehyde by far is the one most extensively used. Applications of the ureaformaldehyde, phenol, and melamineformaldehyde as bonding agents in composite construction materials, thermal insulations, electrical and electronic applications and others, are included in citations from the Rubber and Plastics Research Association Database [8].

Upon full polymerization, ureaformaldehyde yields a highly cross-linked thermosetting product which is insoluble and infusible. Cross-linking is derived from strong chemical bonds connecting the polymer chains. As network structures develop through cross-linking, strength continues to build-up. The fully cured resin is characterized by a high modulus and strength, low creep and good elevated temperature stability. Apart from these qualities, ureaformaldehyde polymers are highly economical, light in colour, lack odour, and are non-toxic. In an independent study, the durability of the investigated polymer concrete under different environmental conditions has been examined in detail by Alp *et al.* [9] and found to retain excellent water repellence and acceptable strength after about 3 years' exposure in an aqueous environment and under solar radiation, respectively.

2. Materials

The constituents used to produce the polymer concrete consisted of mixed siliceous aggregates having a coarse: fine aggregate ratio of 2:1 by weight and a ureaformaldehyde resin of 55% solid content.

2.1. Ureaformaldehyde

In this investigation, the ureaformaldehyde used was in the form of a white viscous resinous liquid. The resin had a solid content of 55%, a density of 1.238 g cm⁻³ at 20°C, a viscosity of 19.2 in./122 cP according to DIN specification (at 20°C), and a reactivity of 50 sec at 100°C. The resin contained 0.55% free formaldehyde. As received, the resin had a pH of 8.11 at 20°C. The 55% resin may be safely stored for a period of 3 mo at 20°C or a longer period when refrigerated.

2.2. Aggregate

The fine aggregate was brought from Wadi Noman, 30 km north-east of Makkah, Saudi Arabia, sieved on

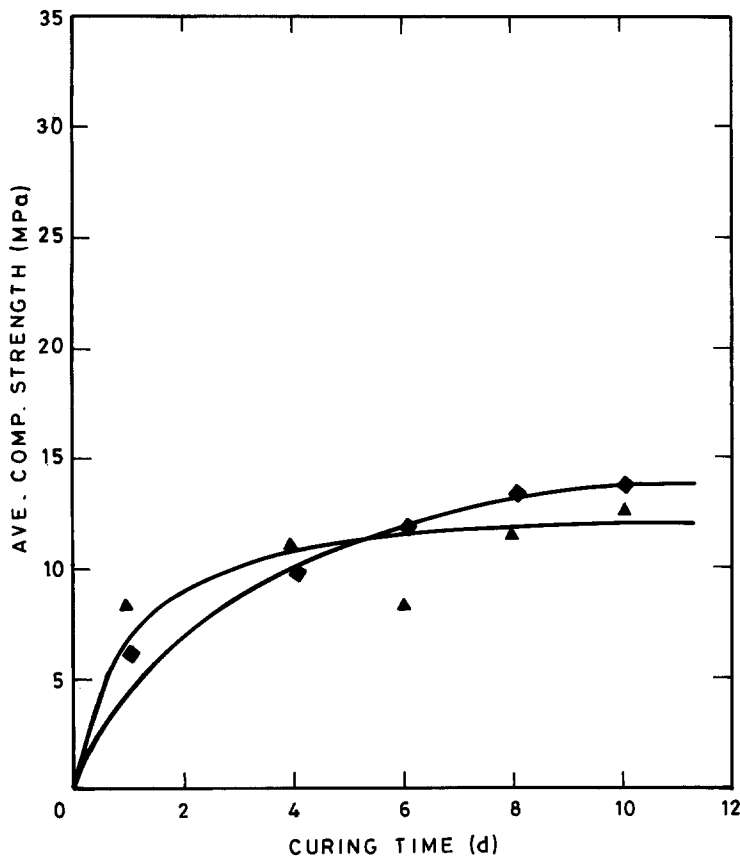


Figure 1 Average compressive strength plotted against curing time of polymer concrete with 6% resin content. Curing temperature: (◆) 100°C, (▲) 110°C.

Sieve no. 4 and washed through Sieve no. 200 to remove any water-soluble matter. X-ray diffraction carried out to determine its mineralogical composition, showed basically feldspar and quartz with traces of hornblende and mica. It had a water absorption of 2.3% with apparent, saturated surface dry (SSD), and bulk specific gravities of 2.642, 2.661 and 2.706, respectively. A minimum of 250 grains were viewed in groups of 50 grains through a microscope for estimates of average sphericity and roundness of 0.81 and 0.48, respectively.

The coarse aggregate, obtained from the Jeddah area, had a maximum aggregate size of $\frac{3}{8}$ in. It was mainly quartz, feldspar, hornblende, plasioclase, and holloysite. The bulk unit weight was 1695 kg m^{-3} with water absorption of 1.22%. The apparent, SSD, and bulk specific gravities were 2.81, 2.85, 2.91, respectively, with an impact value of 6% and Los Angles abrasion value of 18%.

3. Specimen preparation procedure

Prewighed quantities of the constituents were mixed for a sufficient period of time to obtain a homogeneous mix without running into the risk of gelling prior to polymerization heat treatment. The mix produced was cast into 100 mm × 100 mm × 100 mm moulds. Each specimen was prepared by forming three layers, each manually tamped 35 times by a standard rod, in conformity with ASTM specification C-192 and BS 1881: Part 3.

Curing was carried out in an electrically heated oven held at a constant temperature, which was monitored by a thermocouple potentiometer apparatus. For the purpose of comparison, five curing temperatures, 90, 100, 110, 130 and 150°C, were selected.

After the first 24 h curing the cured-specimen assemblies were removed from the oven and cooled for 1 h. Then, the semi-cured specimens were removed from the moulds for improve heat transfer, and readmitted to the oven for polymerization to proceed to completion. No external pressure was applied during removal of specimens from the moulds. The rest of the curing cycle was now continued by exposing the naked specimen surfaces directly to the atmosphere in the universal oven chamber in order to ensure an efficient heat transfer and facilitate water removal from the interior of the specimens.

Four different resin contents were chosen for strength optimization purposes. The resin content is defined as the ratio of the total weight of the ureaformaldehyde to the combined weight of fine and coarse aggregate. The selected ratios were 6%, 8%, 10% and 13.3%, respectively.

4. Discussion

The results of the compression tests are expressed in the form of average compressive strength–curing time plots for each curing temperature and resin content. Each data point represents an average compressive strength of at least three individual specimens subjected to identical conditions. It was found that a mix with 13.3% resin content formed a sloppy consistency. At 90°C, the polymerization process was incomplete and the cured specimens were inferior in strength. Variation of the average compressive strength with curing periods for a resin content of 6% and curing temperatures of 100 and 110°C is shown in Fig. 1. For 8% and 10% resin contents, the average compressive strength for various curing temperatures is shown in Figs 2 and 3, respectively. The effect of resin content

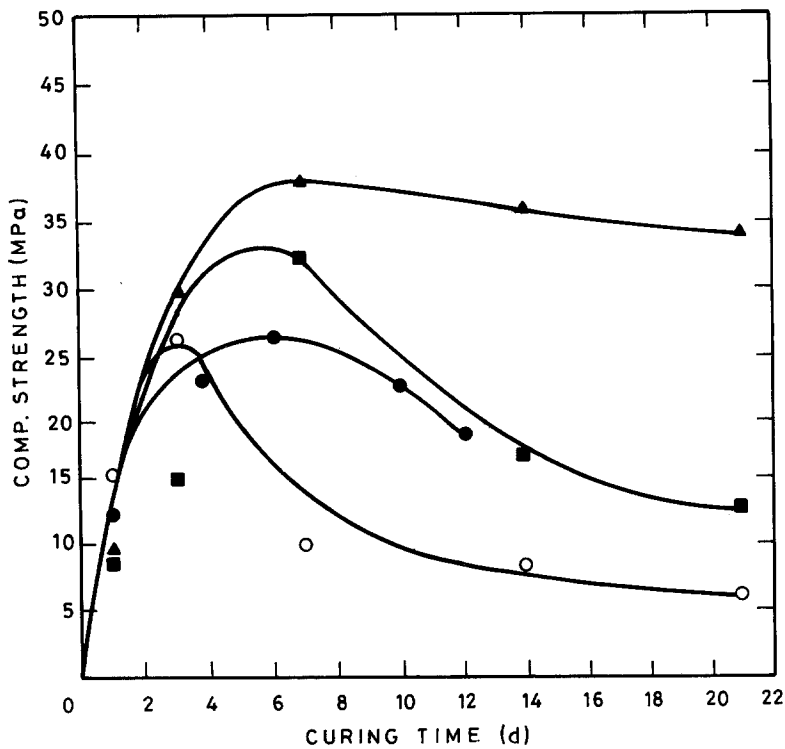


Figure 2 Average compressive strength plotted against curing time of polymer concrete with 8% resin content. Curing temperatures: (●) 100°C, (▲) 110°C, (■) 130°C, (○) 150°C.

on the compressive strength with curing period at 110°C is shown in Fig. 4.

It is noted that the average compressive strength rises quite steeply with curing time, reaches a maximum, then begins to decline gradually at a rate much slower than its rise. The strength developed in the polymer may be viewed as the algebraic sum of several factors, which proceed simultaneously but at different rates. Up to the maximum, the formation of additional chemical bonds in the resin molecules results in molecular chain growth and cross-linking of the macromolecules. The condensation polymerization has no absolute termination, and cross-linking, therefore, continues over a lengthy period of time [10, 11].

On the other hand, it is well established that urea-formaldehyde shrinks upon polymerization. The amount of linear shrinkage upon heating at 110°C after 3 h is only about 0.1%, while after 10 d is shown to be in the vicinity of 1.4% [12]. With continued shrinkage and cross-linking, the internal stress build-up may exceed the fracture strength of the thin polymer films encapsulating the second-phase particle and a localized rupture of the polymer film may occur leading to a progressive lowering of strength.

It is noted from the above results that a resin content of 8% at a curing temperature of 110°C is found to yield the highest compressive strength of 37.0 MPa. This strength is achieved at a curing period ranging

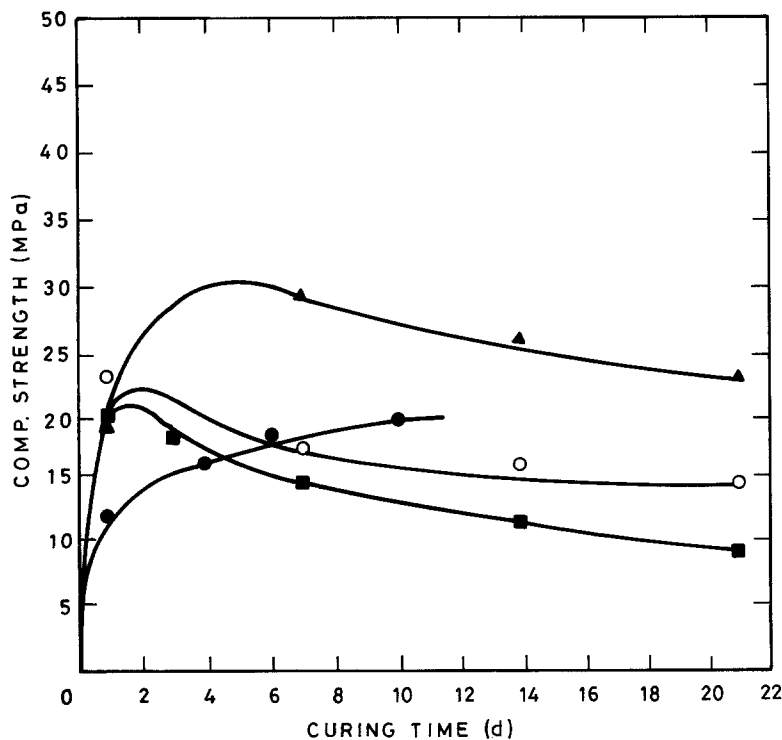


Figure 3 Average compressive strength plotted against curing time of polymer concrete with 10% resin content. Curing temperatures: see Fig. 2.

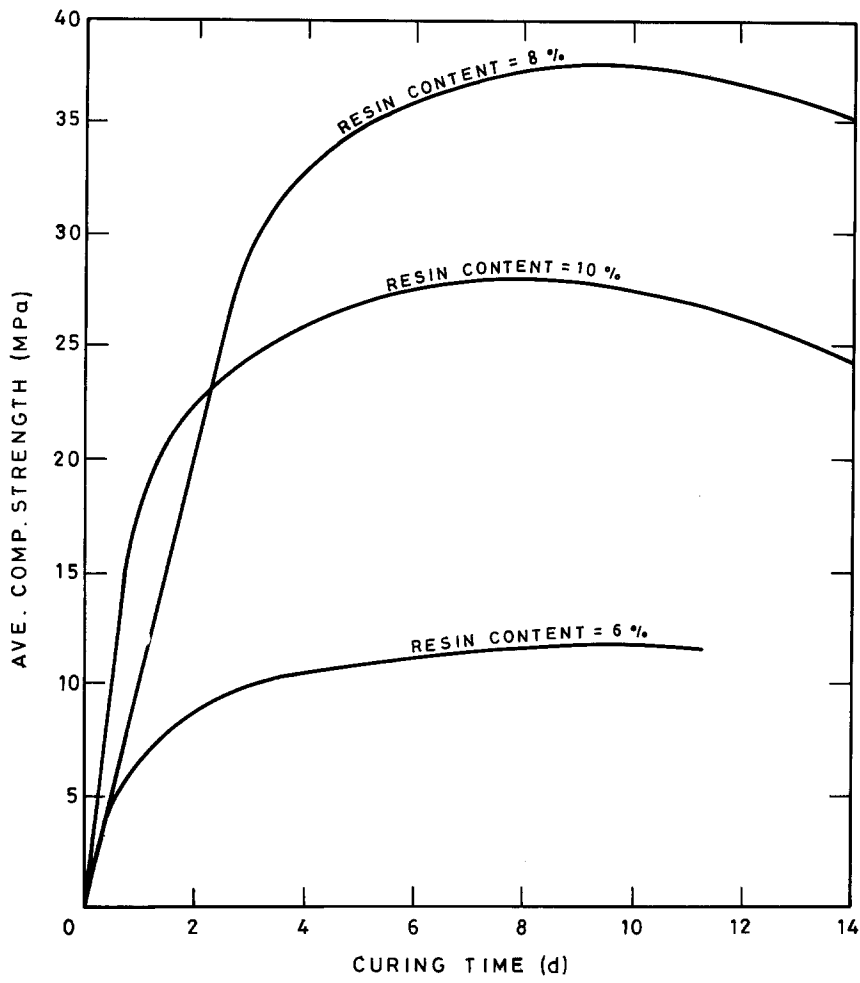


Figure 4 Effect of resin content on the compressive strength of polymer concrete cured at 110°C.

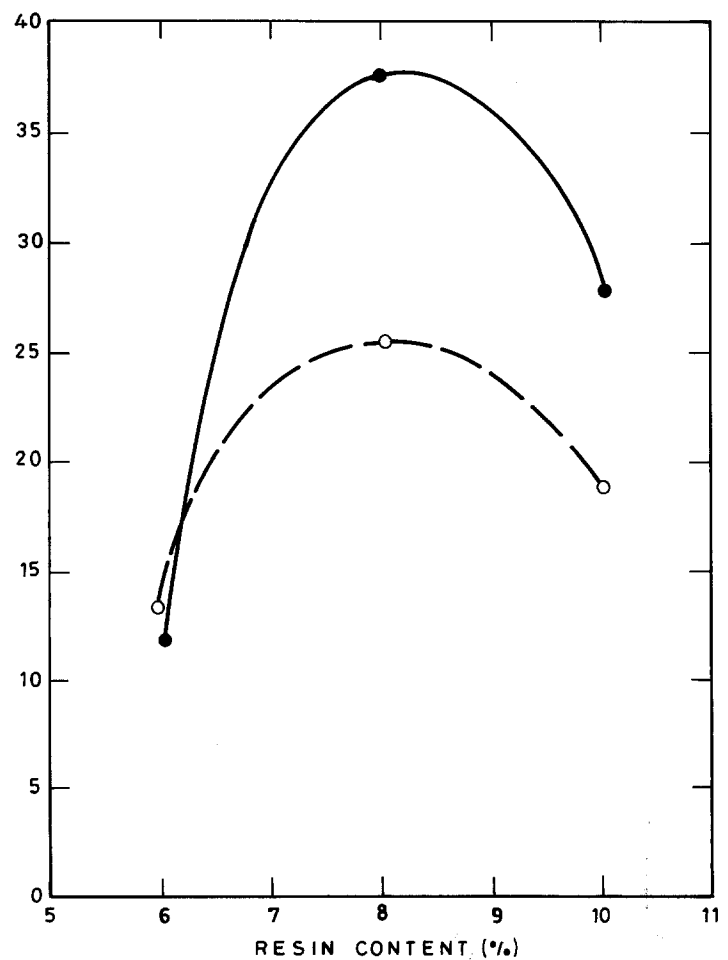


Figure 5 Maximum compressive strength plotted against resin content of polymer concrete cured at (●) 110°C, (○) 100°C.

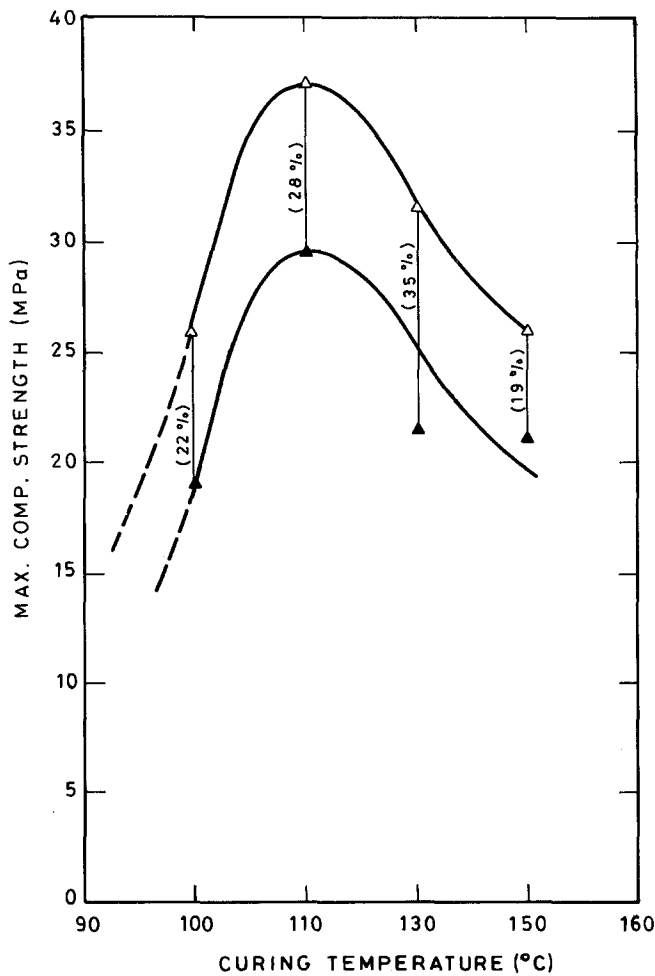


Figure 6 Maximum compressive strength plotted against curing temperature of polymer concrete with different resin contents (Δ) 8% resin, (\blacktriangle) 10% resin. Values in parentheses are per cent reductions.

from 7 to 10 d. The marked influence of curing temperature on the maximum strength is demonstrated in Fig. 5 which represents results of curing at 100 and 110°C. For specimens cured at 110°C, the maximum compressive strength for different resin contents reaches a value of 37.0 MPa at about 8% resin content. Upon curing at 100°C the peak value for the same resin content falls to almost 25.0 MPa, which corresponds to a decrease of approximately 33%. The fact that the strength achieved by curing at 110°C is considerably higher compared to 100°C may be attributed to the accelerating effect of the higher temperature on the kinetics of polymer-chain propagation and higher degree of cross-linking.

The effect of changes in the curing temperatures on the peak strength becomes insignificant for low resin content. The difference between the highest strength levels achieved by curing specimens with 6% resin at 100 and 110°C in Figs 1 and 5 is negligible. Also, as the resin content is increased from 8% to 10% the maximum compressive strength decreased, on the average by about 26% as shown in Fig. 6.

4.1. Comparison between PC and Portland cement concrete

To compare the results obtained from polymer concrete using ureaformaldehyde with that of type I Portland cement concrete (PCC) for the 100 mm \times 100 mm \times 100 mm specimens, two water:cement ratios were used: 0.5 and 0.7, and two mix proportions were tried; 1:1.5:3 and 1:2.5:5. These mixes are commonly

used for general purpose constructions. The average compressive strengths are plotted against curing time for the trial mixes in Fig. 7.

For the selected mixes, polymer concrete gives higher compressive strength for the same type of aggregates, same coarse/fine aggregate ratio, and same binder content. Results from polymer concrete with 8% ureaformaldehyde at 110°C curing temperature give an average compressive strength of 37.0 MPa which is equivalent to a 21 d average compressive strength obtained from PCC with a mix proportion of 1:2.5:5 and a water:cement ratio of 0.5, where the cement content by weight in the PCC is 1:7.5 or 13.3% compared to 8% resin content in the PC. Hence in this case, an additional amount of 66% binder (cement) in the PCC is needed to attain similar PC compressive strength. In addition to this advantage, PCC with a mix proportion of 1:2.5:5 and a water:cement ratio of 0.7 gives a 21 d average compressive strength of only 15.0 MPa, or a 60% decrease compared to the same PC with 8% resin content.

It is also noted that the workability of the PCC with mix proportion of 1:2.5:5 and water:cement ratio of 0.5 is low and the slump is almost negligible. To improve the workability, the cement content is raised to 22.2%, or a mix proportion of 1:1.5:3, and the water:cement ratio is increased to 0.7. The new workability came to be very similar to that of PC. However, the average compressive strength of the PCC in this case is 30.0 MPa, a slight decrease of about 19% compared to PC with 8% resin content cured at 110°C.

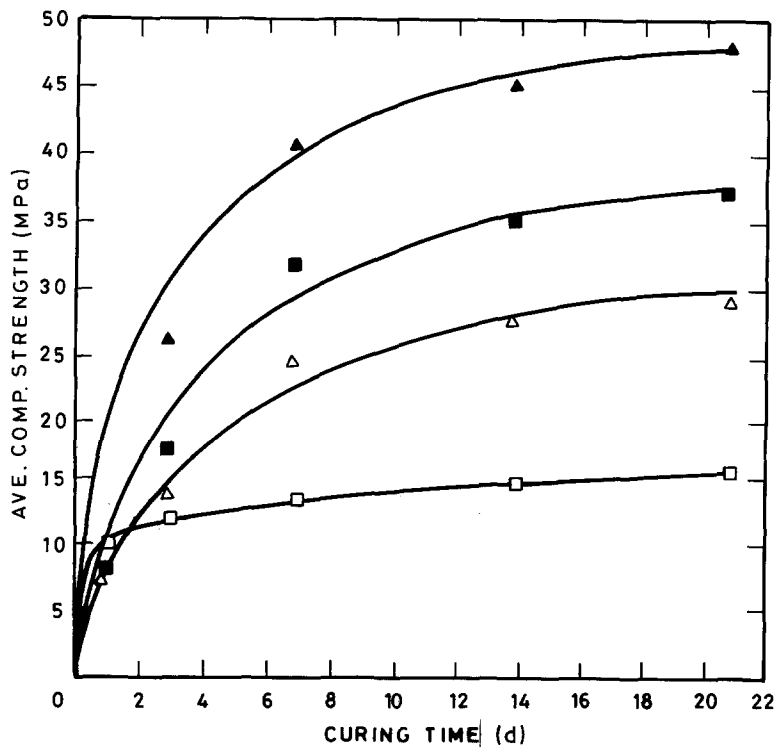


Figure 7 Average compressive strength plotted against curing time of Portland cement concrete, containing no resin. Water: cement ratios and mix proportions, respectively: (▲) 0.5, 1:1.5:3; (■) 0.5, 1:2.5:5; (△) 0.7, 1:1.5:3; (□) 0.7, 1:2.5:5.

5. Conclusions

The results indicated that a polymer concrete with 8% ureaformaldehyde emulsion binder at a curing temperature of 110°C developed an optimum compressive strength of 37.0 MPa in a curing period ranging from about 7 d.

When compared with Portland cement concrete of a similar specimen size prepared at water:cement ratios of 0.5 and 0.7, and mix proportions of 1:1.5:3 and 1:2.5:5, polymer concrete gave higher compressive strength values for the same resin content, same type of aggregates, and same coarse/fine aggregate ratio.

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