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Influence of ambient temperature on early age concrete behaviour of anchorage zones

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HIGHLIGHTS

- This research treats the anchorage zone behaviour post-tensioned slabs exposed to ambient conditions.
- The conclusions from the analytical study will help better predict bearing stresses in early age concrete members.
- The research findings are particularly important for design of post-tensioned members with early age concrete properties.

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ABSTRACT

Many anchorage zone failures of post-tensioned concrete beams and slabs have occured in the recent past, during stressing stage, prompting urgent attention to investigate the performance of anchorage zone concrete at early age. The strength properties of early age concretes at the time of tendon stressing is significantly influenced by the fluctuation of ambient temperatures. The existing design equation for allowable bearing stress is a function of concrete compressive strength at the time of post-tensioning. This paper reports parametric studies based on finite element modelling to investigate the effects of variable temperatures on concrete strength. The model was validated against experimental results. Allowable bearing stresses were calculated from compressive strength results between 1 and 7 days. These allowable bearing stresses can then be compared with average bearing stresses from the post-tensioning load to evaluate the bearing capacity of the local anchorage zone. Based on the illustrative example presented, it is shown that the values of allowable bearing stress can be exceeded at the final stressing stage. Inadequate compressive strength at early age can contribute to failures of anchorage.

1. Introduction

Concretes used in post-tensioned (PT) concrete slabs have early age strength requirements for initial and final stressing processes [1,2]. This is typically at 1-day age for initial stressing and 3–4-days age for final stressing. The age at which the final stressing is applied depends upon a confident prediction of in situ strength. The normal practice in many countries is to use a minimum compressive strength of 22 MPa for final stressing. After successfully transferring the post-tensioning load, the ends of the tendons are permanently anchored to the concrete at specified locations in the member.

Despite the use of high early strength concrete as the obvious choice of construction material, many failures have been observed in the floor at anchorage zones. Naturally, the introduction of concentrated loads into the slab section produces highly concentrated stress regions immediately ahead of, and surrounding, the anchorage plate. Anchorage failures generally occur at the time when the post-tensioning load is being transferred. Sometimes, they appear within a day or two after loading, in the form of a crack that propagates along the centreline of the anchorage zone for an arbitrary length.

A typical dead-end anchorage failure is presented in Fig. 1. Observations of anchorage failures in multi-storey apartments during construction in Canberra and Melbourne have indicated that anchorage failures are mostly localised. Given that the failures occur abruptly, it is very difficult to establish the sequence of failure; and, therefore, it is not easy to establish for certain the causes of failures. However, a combination of concrete crushing immediately ahead of the anchor plate (referred to as the "local zone"), shearing and debonding of the strand and wire (for dead-end anchors) appear to be the most plausible causes. In cases where the failures appear in the form of longitudinal cracks along the line of the tendon, they are most likely caused by transverse

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Fig. 1. Dead-end anchorage failure at the bottom soffit of slab (view from the bottom of the slab).

tensile stresses (or bursting stresses) which occur at some distance ahead of the anchorage plate (referred to as the "general zone"). The focus of this paper is on the evaluation of bearing strength at the "local zone". The evaluation of transverse tensile stresses imposed on the "general zone" is outside the scope of this paper.

The tendon forces are transferred to the concrete using an anchorage device that is often proprietary. They are supplied with special bearing plates that have a complex geometry. Special bearing plates generate very high concentrated bearing pressures on the "local zone". The behaviour of such special bearing plates is not readily evaluated analytically. Therefore, their adequacy must be established by tests [3].

The design equation (Eq. (1)) according to Post-Tensioning Institute (PTI) [4] for basic bearing plates is based on AASHTO [5]. Only the design provision for basic bearing plates which are used in conjunction with minimum local confinement reinforcement (total volumetric reinforcement ratio ρ_s greater than 0.2%) is provided herein.

$$f_{cpi} = 0.75 f'_{ci} (A/A_g)^{0.5} \leqslant 1.5 f'_{ci} \quad (1)$$

where f_{cpi} is the allowable bearing stress under the maximum allowable tendon jacking force ($P_{jack} = 0.6 A_{ps} f'_s$), A_{ps} is the nominal prestressing steel area, f'_{ci} is the characteristic compressive strength of concrete cylinder at the time of tendon stressing, A is the distribution area, A_g is the gross bearing plate area, f'_s is the nominal minimum tensile strength of prestressing steel.

The compressive strength of the early age concretes at the time of tendon stressing is significantly influenced by the fluctuation of ambient temperatures. It is commonly believed that uncertain weather patterns and fluctuating temperatures influence the curing process of concrete.

This paper investigates the effects of temperature variation on the early age properties of concrete which influences the behaviour of the local anchorage zone at the time of post-tensioning. An experimental program which consists of temperature measurement of a block of concrete cured under laboratory conditions and testing of concrete strength properties at early age is presented in Section 3. The degree of reaction approach was adopted to model the age-dependent strength properties of concrete. A finite element model (FEM) simulating the hydration reaction of concrete and temperature development of a concrete block is presented in Section 4. The temperature model was validated by comparison with the experimental data. Parametric studies of the effects of initial temperature and the variation of ambient temperature at early ages on the temperature and strength development properties were conducted based on ambient temperatures measured on two different construction sites in Melbourne, Australia (Section 5). It is noted that the variation of temperature ranging between 10 and 35 °C used in this study represents the temperature variation in temperate zones. Therefore, the outcomes presented in this paper are limited to those regions, although the approach applied and the methodology developed can be adopted for other regions. The in situ compressive strength of concrete at early age was assessed by comparing the allowable bearing strength defined by Eq. (1) with imposed bearing stress at the time of load transfer (Section 6). This paper focuses on the effects of ambient temperature on bearing strength and the adequacy of concrete immediately ahead of the anchor plate. It is noted that there are other possible failure mechanisms surrounding the anchorage zone such as bursting failure. Discussion of these failure mechanisms are outside the scope of this paper.

2. Research significance

As mentioned earlier, catastrophic failures in anchorage regions of post-tensioned slabs and beams have been observed in the recent past. An accurate estimation of strength properties of concrete at early ages is important in assessing its behaviour under post-tensioning load. The strength properties of concrete at early ages depend greatly on the ambient conditions. This study investigates the effects of initial temperature and the daily variation of ambient temperatures on the evolution of strength properties of concrete at early ages. The strength of concrete at early ages is then evaluated by comparison with imposed bearing stress at the time of post-tensioning load transfer. The material presented in this paper should assist designers in assessing the bearing capacity of concrete at the time of pre-stressing in view of the daily ambient conditions. Authors are not aware of any other studies conducted before on bearing capacities of concrete at early age.

3. Experimental procedure

3.1. Strength properties

A total of 70 specimens were tested to establish the material properties of concrete at early ages. Preparation of the test specimens for each test was performed in accordance with the relevant Australian Standard for testing of concrete. The tests included compressive, tensile, flexural strength, modulus of elasticity and Poisson's ratio for the concrete mix. The tests were carried out at 2, 3, 4, 7 and 28 days.

The compressive and indirect tensile cylinders (100 mm diameter × 200 mm height) were cast according to AS 1012.8.1 [6], which sets out the procedure for moulding, compacting and curing of compressive and indirect tensile test specimens. The flexural beams (300 mm × 100 mm × 100 mm) were cast according to the requirements of AS 1012.8.2 [7] for making and curing the test specimens.

All concrete samples were cast using ready mixed concrete, left in their moulds for 24 h under laboratory conditions, then transferred to a lime saturated bath until the time of testing. The samples were subjected to constant temperatures of 23 ± 2 °C in accordance with AS 1012 [8].

The concrete used is based on a common post-tension mix designed for winter conditions, with a characteristic compressive strength at 28 days (f'_c) of 32 MPa. The concrete mix details, which were originally presented in Sofi et al. [9], are presented in Table 1.

Table 1
Concrete mix design.

Mix ingredients		Content
Portland cement content	kg/m^3	305
Fly ash content	kg/m^3	35 (10% Fly ash)
Total cementitious	kg/m^3	340
W/C ratio		0.5
Water reducer	ml/m^3	1360
Accelerator	ml/m^3	1360
Air entraining agent	ml/m^3	0
20 mm aggregate	kg/m^3	550
14 mm aggregate	kg/m^3	550
Washed concrete sand	kg/m^3	770
Slump	mm	80 ± 15