VIII International Conference on Fracture Mechanics of Concrete and Concrete Structures
FraMCoS-8
J.G.M. Van Mier, G. Ruiz, C. Andrade, R.C. Yu and X.X. Zhang (Eds)

EVALUATION OF TIME-DEPENDENT BEHAVIOUR OF COMPOSITE CONCRETE SLABS WITH STEEL DECKING (AN EXPERIMENTAL STUDY)

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Key words: Composite Slabs, Serviceability, Shrinkage, Deflection, Curvature

Abstract: Relatively little research has been undertaken on the time-dependent in-service behaviour of composite concrete slabs with profiled steel decking as permanent formwork and little guidance is available to practicing engineers for predicting long-term deflection. The drying shrinkage profile through the thickness of a slab is known to be greatly affected by the impermeable steel deck at the slab soffit, but this has not yet been quantified satisfactorily. This paper presents the results of long-term laboratory tests on composite slabs subjected to both drying shrinkage and sustained loads.

1 INTRODUCTION

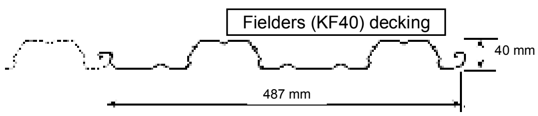
Composite one-way concrete floor slabs with profiled steel decking as permanent formwork are commonly used in the construction of floors in buildings (Fig. 1). The steel decking supports the wet concrete of a cast in-situ reinforced or post-tensioned concrete slab and, after the concrete sets, acts as external reinforcement. Embossments on the profiled sheeting provide the necessary shear connection to ensure composite action between the concrete and the steel deck (Fig. 1b).

Despite their common usage, relatively little research has been reported on the in-service behaviour of such slabs and little design guidance is available to practicing engineers. In particular, the drying shrinkage profile through the slab thickness (which is greatly affected by the impermeable steel deck) and the restraint to shrinkage provided by the deck have only recently been quantified by Gilbert et al. [1]. In their research, Gilbert et al. measured the shrinkage strain variation through the thickness of 5 slabs with different thicknesses that were epoxy coated on 5 sides and were exposed on the top surface to shrink. Although the epoxy coating was not entirely effective to prevent water loss from coated sides, that research clearly showed the nonlinearity of shrinkage strain through the thickness of tested slabs.

Carrier et al. [2] measured the moisture contents of two bridge decks. One of the bridge slabs was 185mm-thick and was placed on profiled steel decking. The other slab was 216mm-thick and was placed on plywood formworks, which were removed after the concrete was placed and cured. In that research it was found that the moisture loss was significant only in the top 50 mm of the slab with profiled steel decking and top and bottom 50 mm of the slab with plywood formworks, regardless of the specimen size.

As a consequence, the techniques used to predict deflection and the on-set of cracking in conventionally reinforced concrete slabs are often applied inappropriately. Although techniques are available for the time-dependent analysis of composite slabs (Gilbert and Ranzi [3]), due to lack of guidance in codes of practice, structural designers often specify the decking as sacrificial formwork, in lieu of expensive timber formwork and falsework, and ignore the structural benefits afforded by the composite action. This provides a conservative estimate of strength, but may well result in a significant under-estimation of deflection because of the shrinkage gradient and the restraint provided by the deck.

(a) Soffit of a one-way slab and beam floor system.



(b) Alternative steel decks showing embossments.

Figure 1: Profiled steel decks for composite slabs (Fielders Australia).

In this paper, the results of an experimental study of the long-term deflection of composite concrete slabs under sustained loads are presented. Deflections caused by creep of the concrete and the effects of drying shrinkage are reported and discussed.

2 EXPERIMENTAL PROGRAM

2.1 Overview

The experimental program involved the testing of ten large scale simple-span composite one-way slabs under different sustained, uniformly distributed service load histories for periods of up to 240 days. Two different decking profiles supplied by Fielders Australia [4] were considered (KF40 and KF70 as shown in Fig. 1b).

The creep coefficient and drying shrinkage strain of the concrete were measured on companion specimens cast with the slabs and cured similarly. Additionally, the compressive strength and the elastic modulus of concrete at the age of first loading and at the end of the sustained load period were measured on standard 100 mm diameter cylinders; while the concrete flexural tensile strength (modulus of rupture) was measured on 100 mm by 100 mm by 500 mm concrete prisms. The elastic modulus E_s and the yield stress f_y of the steel decking were also measured on coupons cut from the decking.

Crack locations and crack widths were recorded throughout the long-term test, together with the time-dependent change in concrete and steel strains, mid-span deflection and the end slip between the steel decking and the concrete.

The objectives of the experimental program were to obtain benchmark, laboratory-controlled data on the long-term structural response of composite slabs under different sustained service loads, in particular the time-varying deflection, and to analyse the effect of creep and shrinkage on the long-term behaviour of composite slabs. The laboratory data will be used to validate analytical models for the prediction of time-dependent behaviour (Gilbert and Ranzi [3] and Gilbert et al. [1]) and to assist in the development of design-oriented procedures to assess the serviceability of composite slabs.

2.2 Test Specimens

Each slab was 3300 mm long, with a cross-section 150 mm deep and 1200 mm wide, and contained no reinforcement (other than the external steel decking). Each slab was tested as a single simply-supported span. The centre to centre distance between the two end supports (one hinge and one roller) was 3100 mm. Five identical slabs with KF70 decking were poured at the same time from the same batch of concrete. An additional five identical slabs with KF40 decking were poured at a different time from a different batch of concrete (but to the same specification and from the same ready-mixed concrete supplier). For both types of steel decking, the thickness of the decking steel was t_s = 0.75 mm.

The cross-section of each of the five slabs with KF70 decking is shown in Fig. 3a.

The composite slabs were cast with the profiled sheeting at the slab soffit continuously supported on the laboratory floor and with timber side forms. A photograph of the KF70 slabs immediately after finishing the wet concrete is shown in Fig. 3b.

Each slab was covered with wet hessian and plastic sheets within four hours of casting and kept moist for six days to delay the commencement of drying. At age 7 days the side forms were removed and the slabs were lifted onto the supports. Subsequently the slabs were subjected to different levels of sustained loading by means of different sized concrete blocks. A photograph of the five KF70 slabs showing the different loading arrangements and the slab designations are shown in Fig. 3c. The first digit in the designation of each slab is the specimen number (1 to 10) and the following two letters indicate the nature of the test, with LT for long-term. The next two numbers indicate the type of decking (with 70 and 40 for KF70 and KF40, respectively). The final digit indicates the approximate value of the maximum superimposed sustained loading in kPa.

The section properties of the steel decking profiles are provided in Table 1 and the self-weight and cross-sectional properties of the composite slabs are given in Table 2.

Table 1: Properties of deck profiles.

Deck Profile Type	Deck thickness t_s (mm)	Section Area A_s(mm^2/m)	Centroid Height y_{sh}(mm)	Mass (kg/m^2)	I_{xx} (mm^4/m)
KF-70	0.75	1100	27.7	9.17	584000
KF-40	0.75	1040	14.0	8.67	269000

Table 2: Properties of composite slabs.

Slab Deck Profile	Specimen Self-Weight (kN/m)/(kPa)	Gross Section $(I_{xx})_{gross}$ (mm^4)	Cracked Section $(I_{xx})_{cr}$ (mm^4)
KF-70	3.60/3.00	278 x 10^6	102 x 10^6
KF-40	3.89/3.24	310 x 10^6	111 x 10^6

2.3 Instrumentation

The mid-span deflection of each slab was measured throughout the sustained load period with dial gauges at the soffit of the specimen. Dial gauges were also used to measure the slip between concrete and steel deck at the ends of the slab at both roller and hinge supports in all slabs.

At mid-span of each slab, the concrete strains were measured using 60 mm long strain gauges on the top and bottom surface. The strain gauges were glued onto the concrete surface and steel sheeting after removing the wet hessian at age 7 days. For slabs 2LT-70-3, 5LT-70-8, 7LT-40-3 and 9LT-40-6 internal embedded wire strain gauges were used to measure the concrete strains at different depths through the thickness of the slab, with locations shown in Fig. 2.

The location, height and width of cracking were measured and recorded throughout the test. Of particular interest was the time-dependent development of cracking and the increase in crack widths with time. Crack widths were measured using a microscope with a magnification factor of 40.

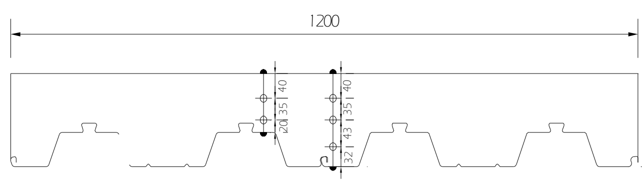


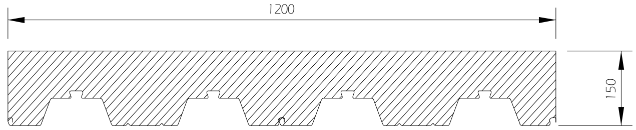
Figure 2: Cross-section showing position of strain gauges in 2LT-70-3 and 5LT-70-8.

2.4 Loading Procedure

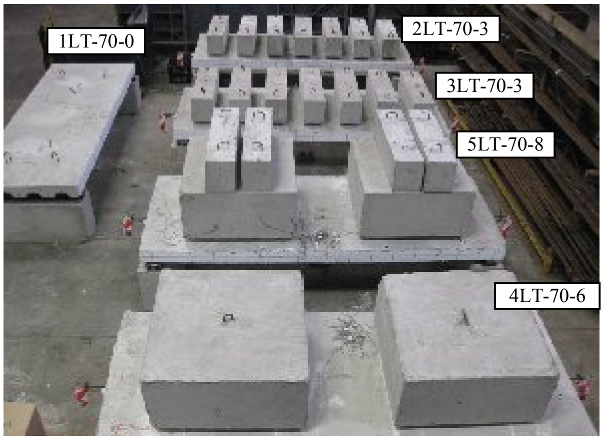
Each of the KF70 slabs was placed onto the supports at age 7 days and until age 64 days, each slab carried just its own self-weight (i.e. 3.0 kPa).

At age 64 days, with the exception of 1LT-70-0, each slab was subjected to superimposed sustained loads in the form of concrete blocks. The block layouts are illustrated in Fig. 4 (and are also shown in Fig. 3c).

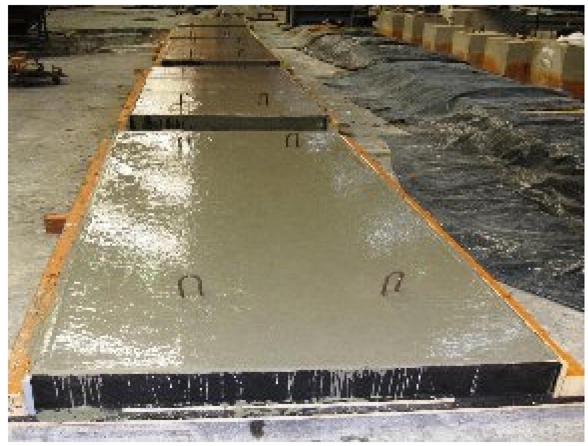
Slab 1LT-70-0 carried only it's self-weight for the full duration on the 240-day test. Slabs 2LT-70-3 and 3LT-70-3 were identical, carrying a constant superimposed sustained load of 3.4 kPa from age 64 days to 247 days (i.e. a total sustained load of 6.4 kPa).



(a) Cross-section.



(c) Slabs with KF70 decking under sustained load.



(b) Slabs immediately after finishing the fresh concrete.

Figure 3: Cross-section and view of KF70 slabs.

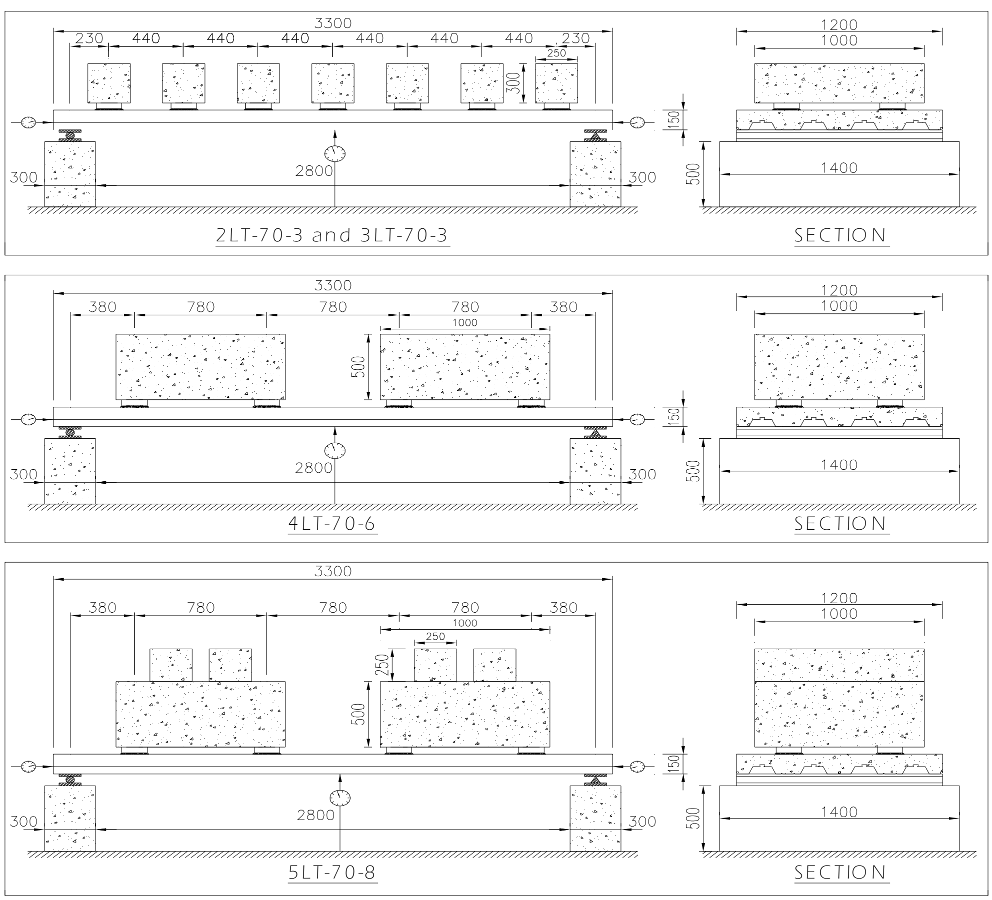


Figure 4: Sustained load configuration for KF-70 slabs.

Slab 4LT-70-6 carried a constant superimposed sustained load of 6.0 kPa from age 64 days to 247 days (i.e. a total sustained load of 9.0 kPa). Slab 5LT-70-8 carried a constant superimposed sustained load of 6.1 kPa from age 64 days to 197 days (i.e. a total sustained load of 9.1 kPa) and from age 197 days to 247 days the superimposed sustained load was 7.9 kPa (i.e. a total sustained load of 10.9 kPa).

Each of the KF40 slabs was placed onto the supports at age 7 days and until age 28 days, each slab carried just it's own self-weight (i.e. 3.2 kPa). At age 28 days (after 21 days drying), with the exception of 6LT-40-0, each slab was subjected to superimposed sustained loads with the block layouts similar to that used for the KF70 slabs and shown in Fig. 3c.

Slab 6LT-40-0 carried only it's self-weight for the full duration of the 244-day test. Slabs 7LT-40-3 and 8LT-40-3 were identical, carrying a constant superimposed sustained load of 3.4 kPa from age 28 days to 251 days (i.e. a total sustained load of 6.6 kPa). Slabs 9LT-40-6 and 10LT-40-6 were identical and carried a constant superimposed sustained load of 6.4 kPa from age 28 days to 251 days (i.e. a total sustained load of 9.6 kPa).

3 TEST RESULTS

3.1 Material Properties

The measured compressive strength, modulus of elasticity and flexural tensile strength are presented in Table 3.

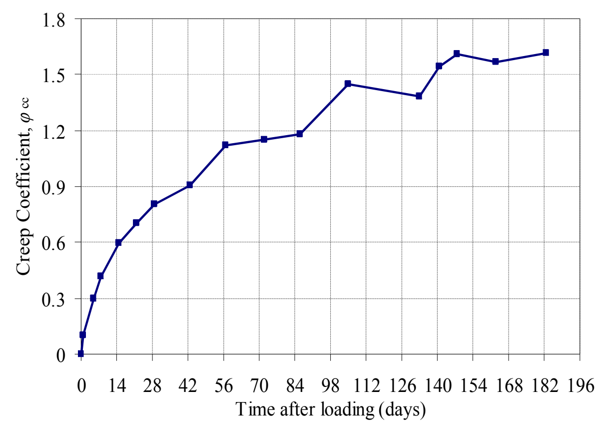
The measured creep coefficient versus time curve for concrete cylinders cast with the KF70 slabs and first loaded at age 64 days is shown in Fig. 5a. The creep coefficient at the end of test was φ_{cc} = 1.62. For the KF40 slabs, the creep coefficient at the end of the test (age 251 days) for the concrete first loaded at age 28 days was φ_{cc} = 1.50.

Table 3: Concrete properties.

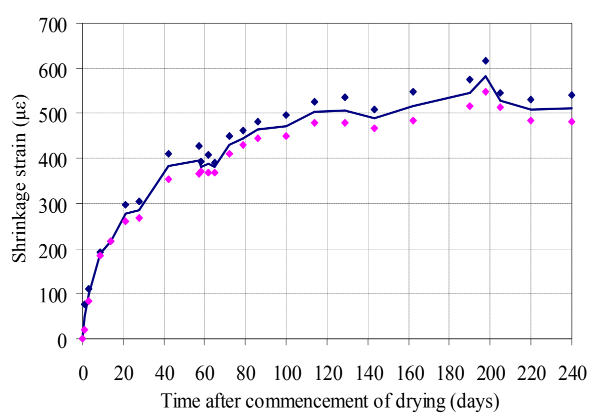
Slab type	f'_c (MPa)		E_c (MPa)		$f_{ct.f}$ (MPa)	
KF-70	64 days	28.0	64 days	30725	64 days	3.50
	247 days	29.8	247 days	31650	247 days	4.54
KF-40	28 days	35.5	28 days	28200	28 days	3.80
	251days	42.70	251 days	31600	251 days	5.05

The development of drying shrinkage strain for the concrete in the KF70 slabs is shown in Fig. 5b. The curve represents the average of the measured shrinkage on two shrinkage prisms (75 x 75 x 275mm) from the day after removing the wet hessian until the end of the test. The average measured shrinkage strain at the end of test was ε_{sh} = 512 με. Similarly, for the KF40 slabs, the average measured shrinkage strain at the end of tests was ε_{sh} = 630 με.

The average of the measured values of yield stress and elastic modulus taken from three test samples of the KF70 decking were f_y = 544 (MPa) and E_s = 212 (GPa), respectively. Similarly, from three test samples of the KF40 decking, average values were f_y = 475 (MPa) and E_s = 193 (GPa), respectively.



(a) Creep coefficient



(b) shrinkage strain

Figure 5: Creep coefficient and shrinkage vs. time curves for concrete in the KF-70 slabs.

3.2 Mid-span Deflection

The variations of mid-span deflection with time for the KF70 and KF40 slabs are shown in Fig. 6 and Fig. 7, respectively. Key deflection values are summarized in Table 4.

These deflections include the deflection caused by shrinkage, the creep induced deflection due to the sustained load (including self-weight), the short-term deflection caused by the superimposed loads (blocks) and the deflection caused by the loss of stiffness resulting from time-dependent cracking (if any). It does not include the initial deflection of the uncracked slab at age 7 days due to self-weight (which has been calculated to be about 0.5 mm for both the KF70 and KF40 slabs).

3.3 Time-dependent Strains

The measured strain variations with time through the thickness of slabs 2LT-70-3, 5LT-70-8, 7LT-40-3, 9LT-40-6 at mid-span are shown in Fig. 9 and the measured curvatures (κ) at mid-span at selected times for each of the KF70 slabs are given in Table 5.

The measured curvature versus time graphs for the KF 40 slabs are given in Fig. 8.

3.4 Cracking

Because of the steel decking at the slab soffit, it was difficult to inspect for flexural cracking in these simply-supported slabs. None of the slabs exhibited any signs of cracking at first loading. However, time-dependent cracking was observed in all of the KF40 slabs, but these cracks remained fine and well controlled for the duration of the test and remained less than 0.15 mm in width throughout. The final locations of cracks in each of the KF40 slabs are shown in Fig. 10.

No cracking was observed in any of the KF70 slabs at any stage of loading, except for slab 5LT-70-8 where three cracks were detected in the positions shown in Fig. 11 at age 210 days (14 days after the second layer of blocks was placed on the slab and the superimposed load was increased to 7.9 kPa).

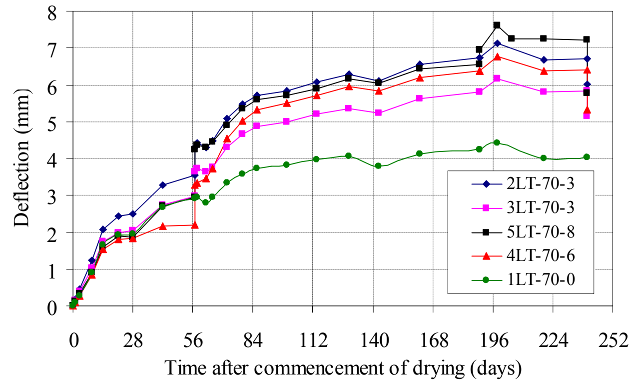


Figure 6: Mid-span deflection vs. time for KF-70 slabs.

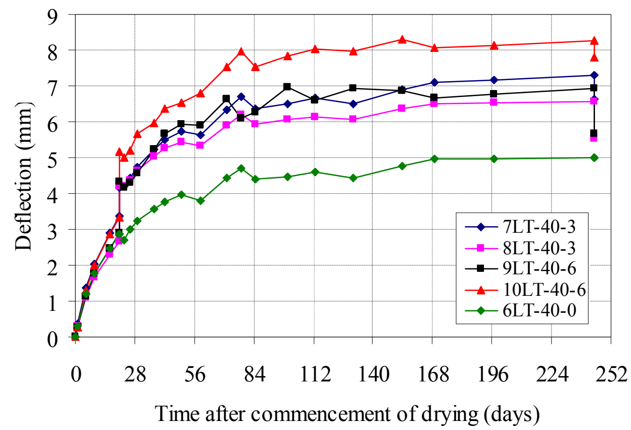


Figure 7: Mid-span deflection vs. time for KF-40 slabs.

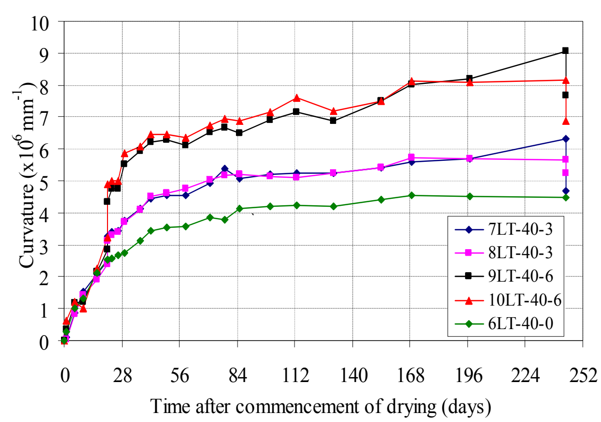


Figure 8: Mid-span curvature vs. time for KF40 slabs.

Table 4: Mid-span deflections.

Slab	Time-dependent deflection (mm)					
	57days of drying		190 days of drying		240 days of drying	
	Before	After	Before	After	Before	After
1LT-70-0	2.92	2.92	4.24	4.24	4.04	4.04
2LT-70-3	3.54	4.29	6.74	6.74	6.72	6.01
3LT-70-3	2.97	3.63	5.80	5.80	5.84	5.16
4LT-70-6	2.18	3.38	6.37	6.37	6.40	5.31
5LT-70-8	2.94	4.23	6.56	6.96	7.23	5.78
	Time-dependent deflection (mm)					
	21 days of drying		28 days of drying	56 days of drying	244 days of drying	
	Before	After			Befor e	After
6LT-40-0	2.83	2.83	3.15	3.87	4.99	4.99
7LT-40-3	3.33	4.14	4.72	5.68	7.30	6.62
8LT-40-3	2.72	4.12	4.70	5.38	6.57	5.53
9LT-40-6	2.95	4.35	4.60	5.90	6.94	5.68
10LT-40-6	3.30	5.10	5.52	6.72	8.26	7.81

Table 5: Curvature at Mid-span deflection at key times.

Slab	Curvature (x10^{-6} mm^{-1})					
	57days of drying		190 days of drying		240 days of drying	
	Before	After	Before	After	Befor e	After
1LT-70-0	1.94	1.94	3.29	3.29	2.92	2.92
2LT-70-3	1.80	2.42	3.83	3.83	3.51	2.98
3LT-70-3	1.89	2.51	3.79	3.79	3.52	2.97
4LT-70-6	1.41	2.85	3.99	3.99	3.83	2.77
5LT-70-8	2.07	2.99	4.55	5.66	5.88	4.42

4 DISCUSSION OF RESULTS

Shrinkage clearly has a dominant effect on the final deflection of these composite slabs. With a sustained load of 3.24 kPa (self-weight), the final deflection of 6LT-40-0 was 4.99 mm. When the sustained load was increased by a factor of about 3 to 9.6 kPa, the slabs suffered additional cracking and yet the final deflection only increased by a factor of about 1.4 to 6.94 mm (9LT-40-6) and by a factor of about 1.7 to 8.26 mm (10T-40-6). A similarly dominant effect of shrinkage over load was observed in the KF70 slabs.

Prior to the application of any load other than self-weight, the slabs deflected significantly, primarily due to the shrinkage induced curvature. For the five KF70 slabs, after 57 days of drying (when ε_{sh} = 400 με), the deflection varied from 2.18 mm (for 4LT-70-6) to 3.54 mm (for 2LT-70-3). Although this was mainly due to early shrinkage, it included the creep deflection resulting from

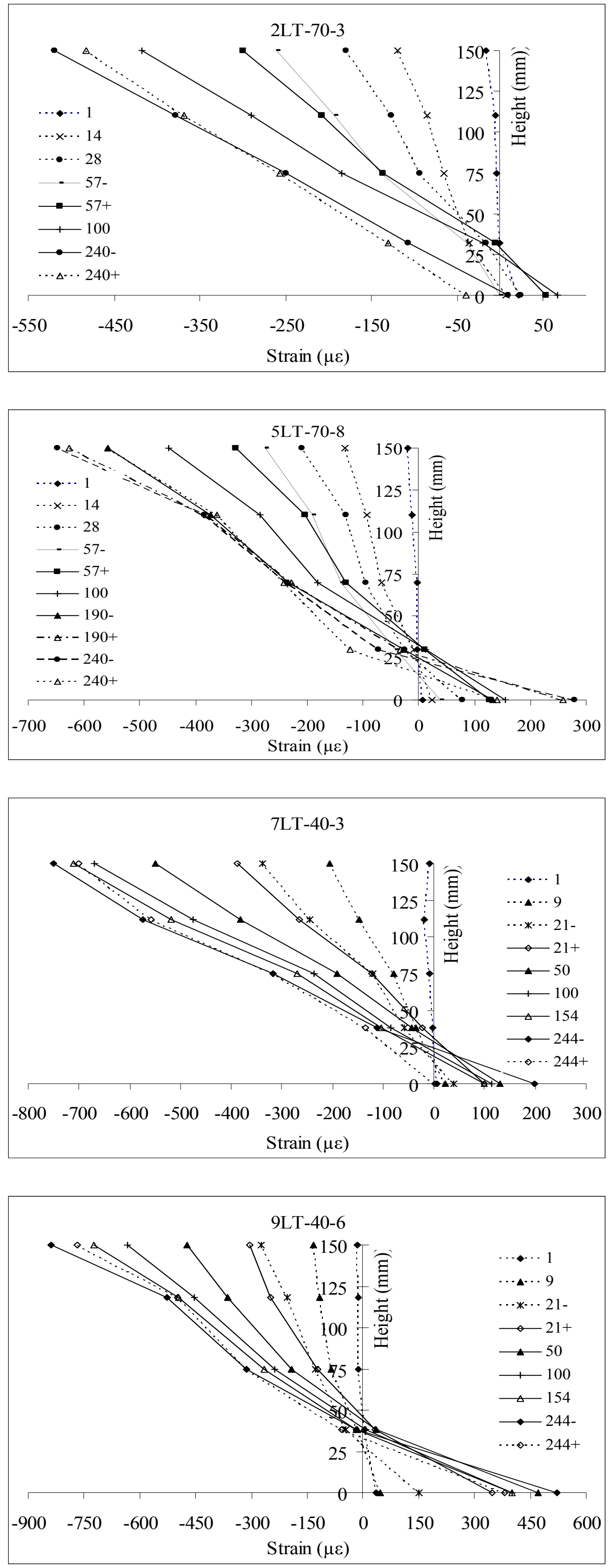


Figure 9: Strains profiles at mid-span (2LT-70-3, 5LT-70-8, 7LT-40-3, 9LT-40-6).

self-weight (estimated at about 0.4 mm). For the five KF40 slabs, after 21 days of drying (when ε_{sh} = 390 με), the deflection varied from 2.72 mm (for 8LT-40-3) to 3.33 mm (for 7LT-40-3).

The difference in the extent of time-dependent cracking between the KF70 slabs and the KF40 slabs was somewhat unexpected. The tensile force that developed with time on the concrete, due to the restraint provided by the KF40 decking to drying shrinkage, was significantly more eccentric to the centroid of the concrete than that provided by the KF70 decking. This may have contributed to the observed differences in crack patterns.

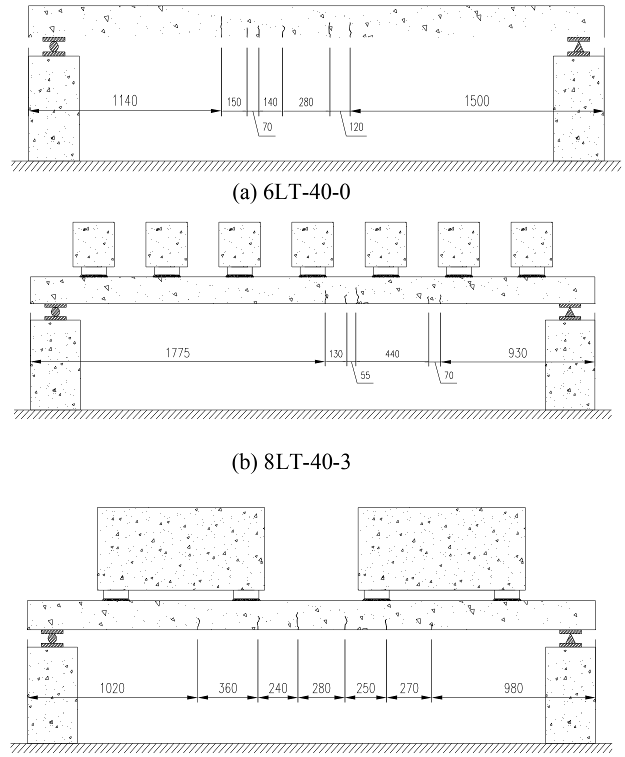
5 CONCLUDING REMARKS

The results of an experimental study of the long-term deflection of composite concrete slabs under sustained loads have been presented. Deformation caused by applied load, creep of the concrete and the effects of drying shrinkage have been reported and discussed for ten simply-supported slabs, with either KF70 or KF40 steel decking (Fielders Australia [4]), subjected to different loading histories.

The curvature induced by the shrinkage gradient resulting from both non-uniform drying and restraint by the steel decking was quantified in a recent paper by the authors (Gilbert et al. [1]). The slab deflections measured in this study have confirmed the dominant effect of drying shrinkage over load for normal levels of sustained loads.

6 ACKNOWLEDGMENTS

The work has been undertaken with the financial support of the Australian Research Council through Linkage Project LP0991495, decking manufacturer Fielders Australia PL and Prestressed Concrete Design Consultants (PCDC). This support is gratefully acknowledged.



(a) 6LT-40-0

(b) 8LT-40-3

(c) 9LT-40-6

Figure 10: Observed crack locations in the KF40 slabs.

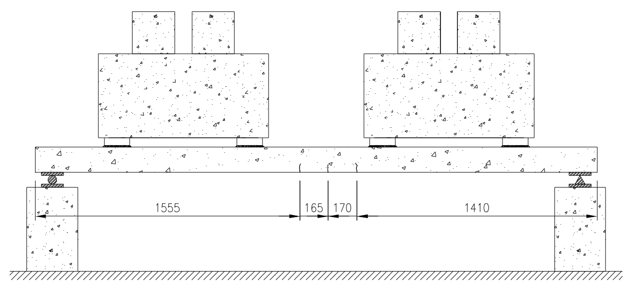


Figure 11: Observed crack locations in 5LT-70-8.

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