STUDY REPORT

SR 340 (2015)

Revisiting concrete ground floor slabs

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The work reported here was jointly funded by BRANZ from the Building Research Levy, the Ministry of Business, Innovation and Employment and the companies whose logos are shown above.

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Preface

This report was prepared following an investigation into shrinkage cracking of concrete floor slabs.

Acknowledgments

This work was funded by the Building Research Levy.

Note

This report is intended for researchers and for general interest.

Revisiting concrete ground floor slabs

BRANZ Study Report SR 340

RH Shelton

Reference

Shelton, R.H, 2015. Revisiting concrete ground floor slabs, Study Report SR340SR340. Building Research Association of New Zealand, Judgeford, New Zealand.

Abstract

This research was initially to gain an understanding of why concrete ground floor slabs crack as a result of concrete drying shrinkage.

The hypothesis was that, by reducing or mitigating the effects of drying shrinkage, the current procedure of cutting the main structural member of the building into smaller sections could be eliminated. This would result in cost savings and substantial improvement in performance.

The study measured restraint to shrinkage movement generated by underslab friction and the perimeter edging, therefore enabling analytical studies of real slab shrinkage to be undertaken. It was found that concrete stresses caused by direct shrinkage were considerably less than those caused by curling due to differential shrinkage between the top and bottom of the slab.

The project also investigated a potential reduction in curling stresses by introducing a drainage layer under the slab. This showed that the drainage layer was unable to provide the required drainage path, and curling was essentially the same as the control slabs.

The overall conclusion of the project was that minimising shrinkage cracking was only possible by good concrete mix design and good workmanship, which are well documented already.

Proprietary methods of reducing shrinkage such as shrinkage-compensating cement, shrinkage-reducing admixtures, steel-fibre reinforcing or post-tensioning were not investigated in the study.

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1. INTRODUCTION

In New Zealand, we have been building on concrete ground floor slabs since the early 1900s. However the popularity of the system only began to rise in the 1950s and 1960s. This was due to the availability of ready-mixed concrete and promotion of concrete floor slabs by the New Zealand Portland Cement Association (New Zealand Portland Cement Association 1975; Building Research Association of New Zealand 1972; New Zealand Technical Correspondence Institute 1969).

Concrete slab floors were easy to place and eliminated the need for high foundation walls. From the design perspective, all rooms could open directly to outdoors without the need for steps. They were vermin-proof, and they were considered to be warmer, quieter and less draughty than suspended timber floors.

Construction details varied until things settled down with the publication of the first NZS 3604 in 1978 (Standards Association of New Zealand 1978). There has been very little change to the basic floor slab details since then.

The Darfield earthquake in September 2010 awakened interest in concrete floor slabs, primarily because of the damage to timber-framed buildings caused by liquefaction and lateral ground spreading. However, it was noticeable that, if the slab remained intact, the damage to the building was relatively light. Conversely, if the slab failed as a result of ground movement, the damage to the building was so costly to repair that frequently the only option was demolition.

This highlighted the conflict between maintaining the continuity of the main structural member of the timber framed building, and the need to break it into smaller sections to relieve the effects of concrete shrinkage. This is typically done by saw cuts and free joints. The hypothesis of this project therefore was to examine if there was another way to mitigate the effects of shrinkage so this conflict could be avoided.

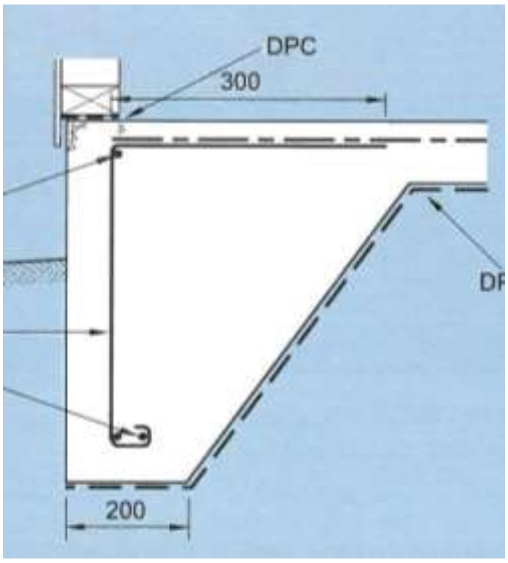
1.1 Background

Until the series of earthquakes in Canterbury in 2010/11, residential floor slabs on ground were built generally in accordance with NZS 3604. Although there are local variations, the essential features of these slabs are as follows:

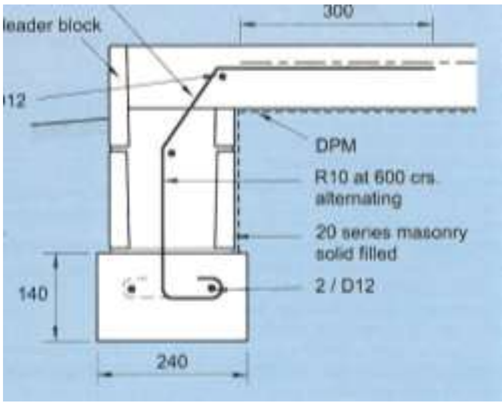
- The site is levelled, and topsoil and organic material are removed.
- Hardfill material is laid and compacted.
- Damp-proof membrane (DPM), usually polythene, is laid on the hardfill, sometimes on a thin layer of blinding sand. Sheet joints are usually adhesive taped.
- A layer of hard drawn wire mesh is placed on the DPM supported on chairs. (It was common practice to omit this reinforcing in some localities and by some builders.)
- 100 mm of residential grade concrete (17.5 MPa) is placed and levelled.
- Control joints are formed by saw cutting, desirably within 12 hours of casting.
- The concrete surface is power trowelled to achieve a smooth surface.
- Curing is seldom used, although sometimes a water spray is used.

The slab edging supporting loadbearing walls was usually formed as a reinforced thickening to the rest of the slab. When required for a masonry veneer cladding, a recess on the top surface was used for weathering. The slab edge was sometimes formed with concrete masonry blocks as permanent formwork. To support loadbearing internal walls, the slab depth was locally thickened as required.

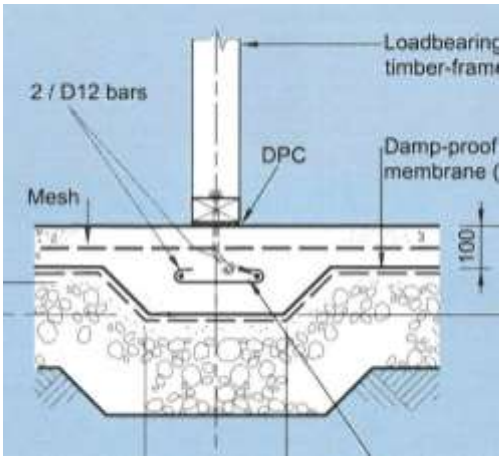
These typical details are shown in Figure 1, reproduced from NZS 3604.



Slab edge formed as slab thickening



Slab edging formed with masonry blocks



Support of load-bearing internal walls

Figure 1. Typical slab foundation details (provided by Standards New Zealand under licence 001175).

In addition, for single-storey buildings, NZS 3604 permitted the use of a ground slab sitting in a recess in the perimeter foundation walls but not otherwise connected to the foundations.

In the 1990s, proprietary voided raft slabs were introduced and have become popular in many areas of the country. However, these slabs are outside the scope of this study.

Slabs were considered as routine elements of the building, with little attention paid to supervision of workmanship. However any variations to the 'standard' foundations would be the subject of a pre-pour inspection by the local building consent authority (the council). The only issues centred around the location and spacing of the control joints, with conflicts between designers wanting joint-free visible spaces and building inspectors policing the provisions of NZS 3604. Compromises here, together with delayed saw cutting and other workmanship issues, frequently led to unintended cracking. Reinforcing mesh was intended to control the severity of this cracking, but little attention was paid to its installation, in particular, its cover from the slab surface. NZS 3604 allowed unreinforced slabs for single-storey buildings provided control joint spacing was reduced. Interestingly, the reinforcing standard for mesh called up by the 2006 amendment of NZS 3604 – AS/NZS 4671:2001 (Standards Australia 2001) – effectively removed the use of hard drawn wire from the scope. Therefore, strictly speaking, no residential floor slabs built between 2006 and 2011 complied with the applicable building standard of the time.

The Darfield earthquake in September 2010 resulted in widespread liquefaction of foundation soils in the eastern suburbs of Christchurch and Kaiapoi, with accompanying lateral spreading in areas close to waterways. The effect on building foundation soils was large differential vertical ground deformations and stretching across cracks in the ground beneath the building. The 'typical' ground floor slab constructed as described above offered very little resistance to these effects, resulting in widespread damage to the slab and, frequently, consequential demolition of the whole building.

Figure 2. Slab cracking as a result of lateral spreading (the Z-shaped crack). Note that part of the crack follows a crack inducer (the fine vertical line).

Reacting to this event, in May 2011, the Department of Building and Housing (now the Ministry of Business, Innovation and Employment) published Amendment 10 to New Zealand Building Code (NZBC) clause B1/AS1. This changed the way NZS 3604 was cited (Department of Building and Housing 2011). Under this amendment, unreinforced slabs and fibre-reinforced slabs (steel or polypropylene) were no longer permitted anywhere in New Zealand, and all concrete slabs had to be tied to their foundations. Slab reinforcing was also required to be ductile, thus confirming the prohibition in the 2006 amendment on the use of hard drawn mesh.

1.2 Previous work

Most research reported in the literature has been about factors influencing concrete shrinkage, how to accurately predict concrete shrinkage, shrinkage restraint and cracking and how to take account of shrinkage in design. Numerous papers cover measurement of shrinkage in the field and in the laboratory, which all stop short of suggesting how to practically accommodate shrinkage in design (Chisholm 2013). Neville (1963) and Neville and Brooks (2010) provide good summaries of the state of the art at the time they were written.

There are few reported studies of shrinkage restraint of ground floor slabs in the engineering literature, and none of the studies focus on New Zealand conditions. Slab/base friction and restraint by foundations are highly dependent on constructional details, and the restraint realistically attainable using New Zealand residential floor slab details is largely unknown. McManus and Burdon (2001) tested more commercial types of foundations for frictional restraint, but this is of limited applicability to typical residential foundation details. Timms (1964) also tested frictional restraint, but this was in a road pavement context.

Therefore, the basis for shrinkage provisions commonly used in New Zealand residential buildings may not be addressing the real issues. However, if conditions and workmanship are ideal, few problems are likely because they have evolved presumably by ‘trial and error’.

2. DEFINITION OF THE PROBLEM

It is well known by the construction industry worldwide that concrete shrinks on drying and that this shrinkage causes cracking of ground floor slabs. This is evidenced by the coverage of the subject in a large numbers of handbooks, magazine articles and ‘how to’ type manuals. Codes of practice, such as NZS 3604, are no exception.

The basic approach is threefold: minimise the concrete shrinkage, add reinforcement and break up the slab into smaller sections by control joints of various kinds.

- Shrinkage minimisation by sound mix design, good workmanship and attention to curing.
- Reinforcement may be added to ‘distribute’ the cracks that inevitably occur. The idea is that, as shrinkage builds up, the tensile stress in the concrete builds up until it cracks. The reinforcing steel transmits the tension across the gap and prevents the crack from widening. As the shrinkage continues, tension builds up again until the next crack occurs, and this process continues until equilibrium has been reached. Thus the cracks remain very fine, regularly distributed and of little practical concern.
- By limiting the length of the slab over which shrinkage can develop, the build-up of tensile stress is reduced. Using control joints or free joints to cut the slab into bays allows a more modest quantity of reinforcement to provide the crack distribution function described above.

Specific requirements in NZS 3604:2011 (as modified by NZBC clause B1 *Structure* Amendments 10, 11 and 12) are to limit slab dimensions to 24 m between free joints or slab edges. A free joint is one detailed to transmit no tensile force across it but to provide for transfer of shear forces. Between free joints, shrinkage control joints are required at a maximum of 6 m spacing. Control joints are typically formed by saw cutting within 24 hours (summer) and 48 hours (winter). Slab reinforcement (ductile mesh or mild steel bars) is required at a rate of 0.00224 mm^2/m^2 (0.224%) in each direction.

The mitigating provisions advocated above, while often proving effective, are not ideal, and lack of real understanding by designers and indifferent workmanship often results in unplanned cracking in any case. If the floor covering is carpet, this is of little consequence, but often the cracking has undesirable consequences.

3. FUNCTION/BEHAVIOUR OF A FLOOR SLAB

To define the problem, it will be helpful to identify the functions of a concrete floor slab and to set out the characteristics of a slab that contribute to that functionality.

3.1 Floor functionality

- The primary function of the ground floor slab is providing a working surface for human activities. In this regard, the concrete slab has superseded earth floors and, to some extent, the traditional tiled or flagged floor. It may be required to provide a substrate for floor coverings such as carpet, thin sheeting, tiles or parquet or may left bare and perhaps polished or coloured. For any of these functions, it is highly desirable that it has no joints or cracks, although it could be argued that carpet is not affected by the presence of cracks.
- The slab contributes to the moisture resistance of the whole flooring system. The primary contribution to moisture resistance is the capillary break from soil moisture provided by a correctly graded hardfill. However, a damp-proof membrane (DPM) laid immediately under the slab provides additional protection.
- An incidental function is to contribute to the thermal insulation of the building, mostly by virtue of the natural insulation of the soil below the slab. However, it is becoming more common to incorporate insulation immediately under the slab, usually using expanded polystyrene sheets.
- The floor slab provides a foundation for constructing timber frames or masonry walls. For this purpose, it must be reasonably level and flat and be able to provide structural anchorage for stability of the superstructure.
- **Structural functions:** The concrete slab provides strength to ‘bridge over’ minor soft spots in the soil below. This is provided by flexural (bending moment) and shear capacity of the slab acting in two-way action.
- The slab also resists direct wind uplift and uplift from the end fixings of bracing walls. This resistance is provided in the first instance by the mass of the slab and foundation and also the pull-out resistance for the hold-down fixings. These are usually bolts in the case of timber or steel framing but also embedment of reinforcing bars for concrete or masonry walls.
- **Additional functions:** It may be supposed that a concrete floor slab will provide resistance to gross ground deformations caused by settlement and also resistance to lateral spreading caused by ground liquefaction. However, as discussed below, its strength (whether reinforced or not) is very limited, and as evidenced by the experience of the Canterbury earthquakes, severe damage is very likely.

3.2 Slab characteristics

- **Flexural strength** is helpful in bridging across soft spots and to a limited extent resisting gross ground deformations. However, as stated above, the flexural resistance of a typical residential floor slab is limited, even when reinforced. Strength depends on the modulus of rupture of the concrete. This can be estimated using formulas given in NZS 3101 (Standards New Zealand 2006) and ACI 318 (ACI Committee 318 2011), based on a specified concrete of 17.5 MPa. Table 1 gives the estimated flexural strength of some examples:

Slab	Flexural strength (kNm per m width)	
	Top in tension (hogging)	Bottom in tension (sagging)
100 mm slab, unreinforced	4.2–6.7 (nil after cracking)	4.2–6.7 (nil after cracking)
100 mm slab, SE62 ductile mesh, 30 mm top cover Steel area – 146 mm^2/m	4.5 (after cracking)	2.3 (after cracking)
100 mm slab, 66-5 hard drawn wire mesh, 30 mm top cover Steel area – 147 mm^2/m	4.6 (after cracking)	2.4 (after cracking)
100 mm slab, D12 bars at 400 mm, 30 mm top cover Steel area – 283 mm^2/m	5.3 (after cracking)	2.7 (after cracking)

Table 1. Characteristics of typical concrete floor slabs.

Note that, because concrete modulus of rupture is a variable quantity, values for a typical range are given (2.5–MPa). Also note the addition of reinforcement has little effect on the flexural strength of the slab, and flexural strength drops after the concrete has cracked under sagging action.

- **Shear strength** is required to resist concentrated loads, usually by resistance to punching shear. Again, reinforcement has little influence.
- **Axial strength** is required to resist stretching due to lateral spreading. However, since liquefaction is excluded from “good ground” as defined in NZS 3604 and modified by B1/AS1, this is outside the scope of the project.
- **Anchor holding** is primarily a function of concrete tensile strength (ACI 355, ACI Committee 355 (2011)). Failure within the concrete itself is typically caused by the induced tensile stresses exceeding the concrete’s tensile stress, typically resulting in the classic cone failure. This mechanism is clearly compromised by the proximity of slab joints.
- **Concrete shrinkage** is one of the most significant characteristics affecting its performance in ground floor slabs. Steps to minimise the effects of shrinkage influence concrete mix design, the curing process, and provision of reinforcement and various types of joints to control cracking. The subject of shrinkage and cracking of floor slabs is discussed in more detail in the next section of this report.

4. ANALYSIS

4.1 Concrete shrinkage

All cementitious products, including concrete, shrink during the drying process.

Shrinkage is simply defined as the reduction in the volume of concrete due to loss of water (Neville and Brooks, 2010). Water may be lost by evaporation, hydration of cement and carbonation.

Soon after casting, while the cement paste is still plastic, it undergoes a volumetric contraction called plastic shrinkage. This contraction is caused by water loss due to evaporation and results in tensile stress cracking on the concrete surface, called plastic cracking. It has no influence on concrete shrinkage.

Drying shrinkage occurs during the hydration process due to the resulting loss of moisture. The process is partly reversible on rewetting, but this is not relevant in the context of concrete floor slabs. The irreversible shrinkage is caused by the chemical reaction taking place during the hardening process.

Carbonation shrinkage is caused by the reaction of the hydrated cement with the CO_2 from the air. Carbonation occurs from the surface inwards and proceeds very slowly.

The factors influencing shrinkage (in roughly decreasing order of importance) are as follows:

- Water content.
- Type and volume of aggregate – since shrinkage takes place in the cement paste, the aggregate effectively offers internal restraint to the concrete. Thus, the greater the volume of aggregate and the higher its modulus of elasticity, the lower the shrinkage.
- Water/cement ratio – the higher the ratio, the higher the shrinkage.
- Relative humidity – the lower the relative humidity during curing, the greater the shrinkage.
- The shape and size of the member may be significant, but this parameter is effectively constant for a floor slab.

Therefore, to some extent, shrinkage can be minimised by suitable mix design and careful workmanship during placing and curing.

Concrete shrinkage can also be minimised by certain proprietary products or systems:

- **Shrinkage compensating cements:** Part of the cement is substituted by an expansion agent, which causes the slab to expand during early curing, thus approximately compensating for the shrinkage.
- **Shrinkage reducing admixtures:** These act by modifying the surface tension inside the cement paste, thus inhibiting the shrinkage mechanism of the concrete.
- **Post-tensioning the slab:** The resulting compression in the slab reduces the tendency for shrinkage cracking.

Although these approaches are all used in the New Zealand commercial field, none are routinely used in residential construction at the time of writing and were outside the scope of the study.

4.2 Shrinkage cracking

Shrinkage of unrestrained concrete is stress free. However, if the concrete is restrained against shrinkage in some way, tension stresses are set up in it. If the stress reaches the tensile strength of the concrete (modulus of rupture), cracking will occur.

In normal floor slab situations, there are several sources of restraint:

1. Reinforcement.
2. Friction between the base of the slab and the soil.
3. Restraint by the bearing of edge foundations and other protrusions into the soil.

Shrinkage strain in the concrete induces compression in the reinforcement and a corresponding tension in the slab. This may be estimated approximately by considering a transformed slab section and equating tension and compression forces together with the bending due to the eccentricity of the reinforcement. Consider 1,000 mm of slab 100 mm thick with 146 mm^2/m of reinforcement at a top cover of 30 mm. Assuming a shrinkage strain of 0.0006 in the concrete, the restraint by the reinforcement induces a tension stress at the top of the slab of 0.37 MPa, which is about 10% of its tensile strength.

There is very little information in the literature quantifying the friction and restraint to concrete floor slabs, and nothing at all covering typical New Zealand slab construction details. To remedy this shortcoming, items 2 and 3 above were quantified experimentally, and this is described in section 5 of this report.

4.3 Simple example slab

To illustrate the effects of these phenomena, the simple floor slab in Figure 3 was analysed. This represents a typical New Zealand ground floor slab of the maximum width for a trussed roof. NZS 3604 would require a saw cut control joint in the middle, but this was omitted for simplicity of analysis.

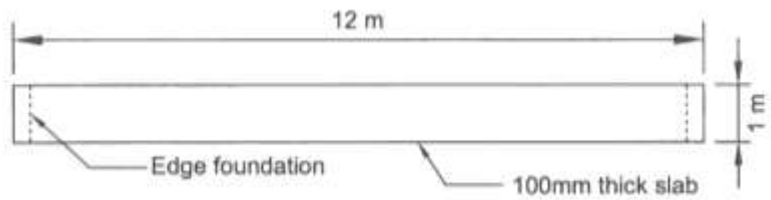


Figure 3. Slab used for analysis.

Concrete compressive strength was taken as 17.5 MPa, the typical strength used for NZS 3604 floor slabs. An estimate of its modulus of elasticity, E, and tensile strength, f_t, made according to NZS 3101, is 3320 $\sqrt{f'_c}$ +6900 = 21,000 MPa and 0.36 $\sqrt{f'_c}$, = 1.5 MPa respectively. The shrinkage strain was initially assumed to be 0.0006 mm/mm (600 microstrain).

If unrestrained, the slab would shrink 0.0006 x 12,000 = 7.2 mm.

If fully restrained at the slab ends, the concrete stress is given by:

Stress = E x strain = 21,000 x 0.0006 = 1.26 MPa.

However, the restraint provided by the NZS 3604 slab edge details is well short of full restraint. Also, friction between the underside of the slab and soil provides additional restraint.

To evaluate these effects, the slab was divided into 40 segments, each 0.3 m in length (columns 1 and 2 of Table 2).

In the first analysis step, for a given age after casting, the unrestrained shrinkage strain was calculated for each segment and the resulting displacement accumulated from the midpoint to the edges (column 3). The restraint generated by the edge was determined using the results of the testing described in section 5.4 and the calculated shrinkage displacement from column 3. Next, the friction force generated within each segment was calculated using the test results described in section 5.4 and the calculated shrinkage displacement (column 4). The combined segment forces were then accumulated to the slab mid-point (column 5).

Age:	1 days	Shr. coef:	0.000026	E:	10,219	MPa	Edging:	Masonry
Column	1	2	3	4	5	6	7	8
			Displacements and forces					
	Slab geometry (m)			Restraint force (kN)		Elastic displacement (mm)		
	Dist. from slab centre	Mid point of segment (from centre)	Shrinkage displ. (mm)	Segment friction and edge restraint	Cumulative force on segment	Segment	Cumulative	Net displ. (mm)
Centre	0.00				11.0	0.00322	0.00322	
	0.30	0.15	0.004	0	11.0	0.00322	0.00644	0.001
	0.60	0.45	0.012	0	11.0	0.00322	0.00967	0.005
	0.90	0.75	0.020	0	11.0	0.00322	0.01289	0.010
	1.20	1.05	0.027	0	11.0	0.00322	0.01611	0.014
	1.50	1.35	0.035	0	11.0	0.00322	0.01933	0.019
	1.80	1.65	0.043	0	11.0	0.00322	0.02255	0.024
	2.10	1.95	0.051	0.306	10.7	0.00313	0.02569	0.028
	2.40	2.25	0.059	0.306	10.4	0.00304	0.02873	0.033
	2.70	2.55	0.066	0.306	10.1	0.00295	0.03168	0.038
	3.00	2.85	0.074	0.306	9.8	0.00286	0.03454	0.042
	3.30	3.15	0.082	0.306	9.4	0.00277	0.03732	0.047
	3.60	3.45	0.090	0.306	9.1	0.00268	0.04000	0.052
	3.90	3.75	0.098	0.306	8.8	0.00259	0.04259	0.058
	4.20	4.05	0.105	0.306	8.5	0.00250	0.04509	0.063
	4.50	4.35	0.113	0.306	8.2	0.00241	0.04751	0.068
	4.80	4.65	0.121	0.306	7.9	0.00232	0.04983	0.073
	5.10	4.95	0.129	0.306	7.6	0.00223	0.05207	0.079
	5.40	5.25	0.137	0.306	7.3	0.00214	0.05421	0.084
	5.70	5.55	0.144	0.306	7.0	0.00205	0.05626	0.090
Edge	6.00	5.85	0.152	7.00				0.096

Table 2. Analysis of shrinkage restraint on example slab (shown at age of 1 day).

For the worst case, using masonry slab edges and no blinding sand under the slab, the analyses showed that the highest mid-point force at an age of 1 day was 11.0 kN (shown at the top of column 5), which is equivalent to a tensile stress in the slab of 0.11 MPa. The lowest slab stress, using sloping slab edges with polystyrene, and sand blinding under the slab, was 0.015 MPa. These values may be compared with a tensile strength of 1.51 MPa calculated from NZS 3101 for 17.5 MPa concrete. However, during the early stages of the concrete drying process, the relevant concrete properties (E, ε_{sh} and f_t) are all increasing in magnitude and at different rates.

- Increase of shrinkage with time may be estimated from ACI 209R-92. For typical slab dimensions, humidity of 40%, minimal moist curing, concrete shrinkage strain at time t after initial curing may be estimated from:

$$\varepsilon_{sh,t} = \frac{t}{35+t} \cdot \varepsilon_{sh,u},$$

  where $\varepsilon_{sh,u}$ is the ultimate shrinkage strain.

- The modulus of elasticity, E, of early age concrete was taken from the experimental study by Oluokun et al. (1991).
- Tensile strength, f_t, was also estimated from Oluokun, with the conversion from compressive strength to tensile strength made using NZS 3101 clause 5.2.6:

$$Ft = 0.36 \sqrt{f'_c}.$$

These time-dependent relationships are plotted in Figure 4.

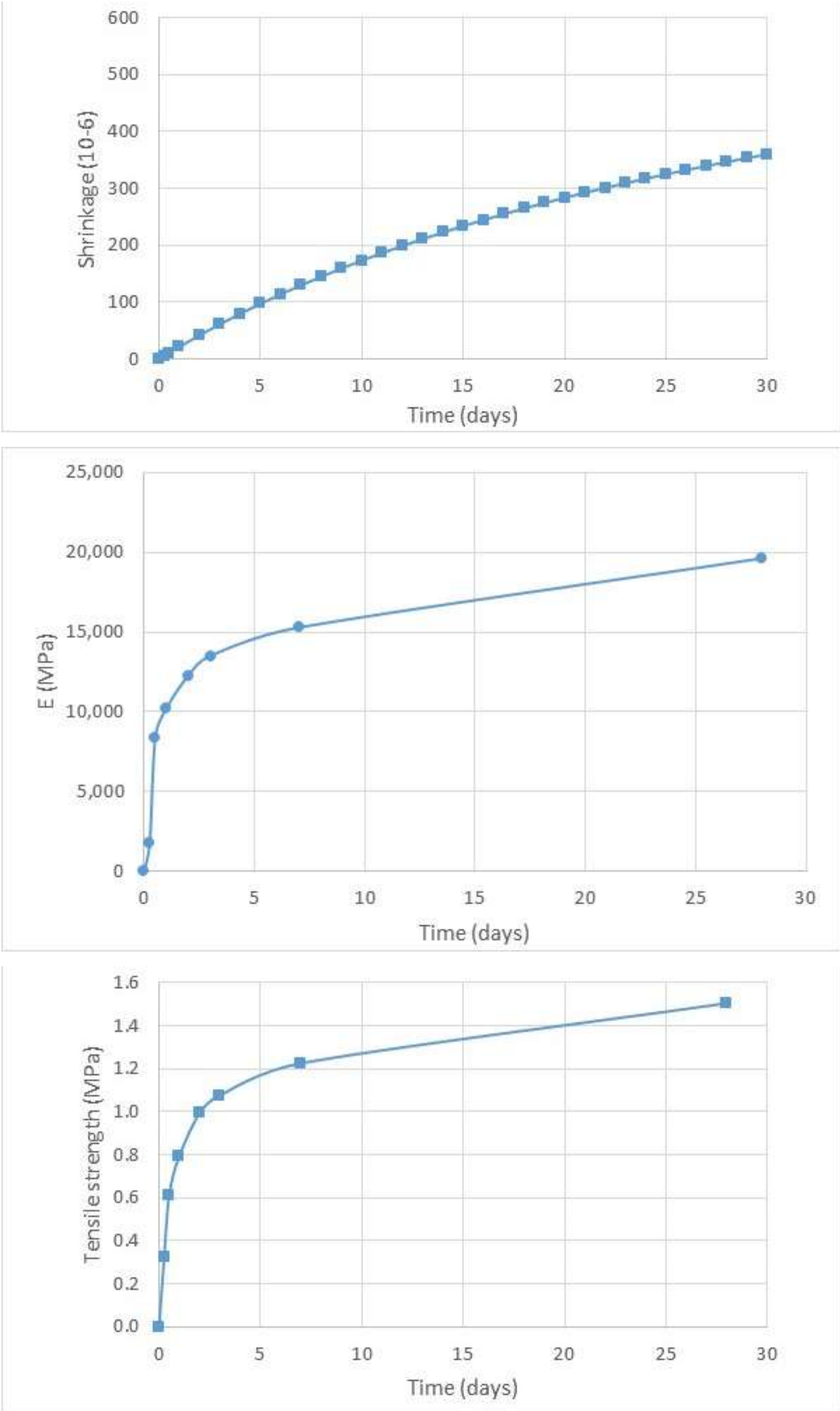


Figure 4. Time-dependent concrete properties – shrinkage (top), modulus of elasticity E (middle), tensile strength (bottom).

The analysis was then repeated for time steps 0.25, 0.5, 1, 2, 3, 7 and 28 days. For each step, concrete shrinkage and E were set to the appropriate value at the corresponding age, and the imposed stress was compared with the calculated tensile strength at the corresponding age. The results are presented in Table 3.

		Sloping edging			Sloping edging (with polystyrene)			Masonry edging		
Age days	ft (MPa)	Force (kN)	Stress (MPa)	Ratio (stress/f_t)	Force (kN)	Stress (MPa)	Ratio (stress/f_t)	Force (kN)	Stress (MPa)	Ratio (stress/f_t)
0	0.00	0.0	0.00	0	0.0	0.00	0	0.0	0.00	0
0.25	0.32	1.17	0.01	0.036	0.39	0.00	0.012	1.79	0.02	0.055
0.50	0.61	2.31	0.02	0.038	0.77	0.01	0.013	3.55	0.04	0.058
1	0.80	4.56	0.05	0.057	1.52	0.02	0.019	7.00	0.07	0.088
2	0.99	7.98	0.08	0.080	4.80	0.05	0.048	15.45	0.15	0.156
3	1.08	11.24	0.11	0.104	9.22	0.09	0.086	24.78	0.25	0.230
7	1.23	15.64	0.16	0.128	14.94	0.15	0.122	31.96	0.32	0.261
28	1.51	19.75	0.20	0.131	18.60	0.19	0.124	35.70	0.36	0.237

Table 3. Shrinkage analyses using time-dependent concrete properties.

It can be seen that the most critical situation is at 7 days with a masonry slab edge where the direct shrinkage-induced stress is approximately 26% of the tensile strength. However, the low ratio of tensile stress does not explain the prevalence of shrinkage cracking of floor slabs.

A possible explanation may lie in the curling action of the slab under differential drying shrinkage. This hypothesis is explored in section 6 of this report.

5. RESTRAINT TESTS

As discussed in sections 1.2 and 4.2, information was needed on the restraint to typical New Zealand slab construction details provided by slab/base friction and by foundations protruding into the ground.

5.1 Test specimens

5.1.1 Slab friction tests

For the friction tests, six test slabs were constructed by a building contractor on a gravel carpark in the BRANZ yard (see Figure 5).

Figure 5. Friction test specimens

The test slabs were 1,500 mm x 1,500 mm x 100 mm thick and were founded on a 100 mm bed of compacted basecourse. All construction details followed the provisions of NZS 3604:2011.

- Two slabs were laid on a 0.25 mm polythene membrane directly on the basecourse.
- Two slabs were laid on a 0.25 mm polythene membrane with a sand blinding layer on the basecourse.
- Two slabs were laid on a double layer of 0.25 mm polythene membrane on a sand blinding layer on the basecourse.
- Two additional slabs were constructed incorporating the slab thickening detail of Figure 7.20 of NZS 3604. One of these specimens was laid on a 50 mm layer of polystyrene insulation (see Figure 6).

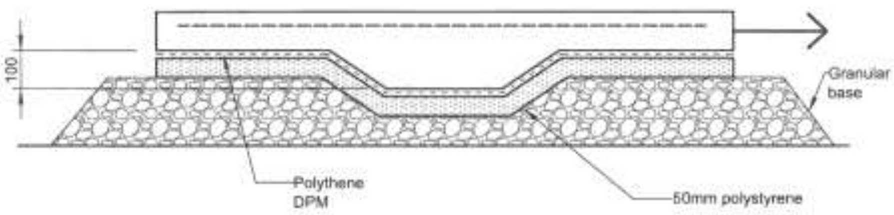


Figure 6. Slab with loadbearing thickening.

The test specimens are scheduled in Table 4.

Configuration	Specimen id.	No. of replicates	Imposed load
Slab on 1 layer polythene directly on basecourse	1	2	0 kg
			375 kg
Slab on 1 layer polythene on blinding sand on basecourse	2	2	0 kg
			375 kg
Slab on 2 layers polythene on blinding sand on basecourse	3	2	0 kg
			375 kg
Slab with load-bearing wall thickening, on polythene directly on basecourse	4	1	0 kg
			690 kg
			1,380 kg
Slab with load-bearing wall thickening, on polythene, on polystyrene, on basecourse	4a	1	0 kg
			690 kg
			1,380 kg

Table 4. Slab configurations tested.

5.1.2 Slab edging tests

For the slab edging tests, four slabs were constructed by a building contractor on a cleared site in the BRANZ yard. They were 1,500 mm x 1,000 mm x 100 mm thick with integral edging. All details followed the provisions of NZS 3604 (see Figure 7).

Figure 7. Slab edge specimens after casting.

Three specimens followed Figure 7.13 of NZS 3604. One of these included a 50 mm layer of polystyrene on the sloping ground surface (see Figure 8).

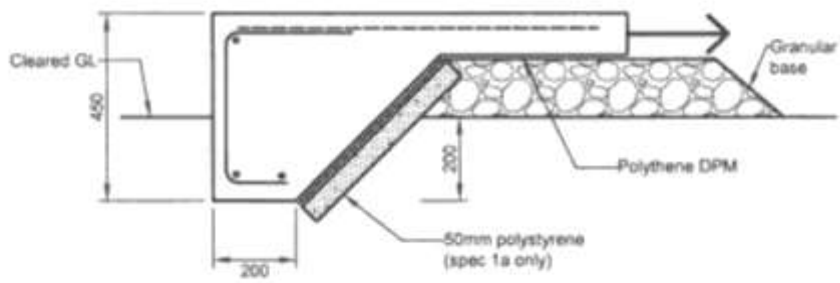


Figure 8. Slab edge specimens 1 and 1a.

One specimen followed Figure 7.14 of NZS 3604 (see Figure 9).

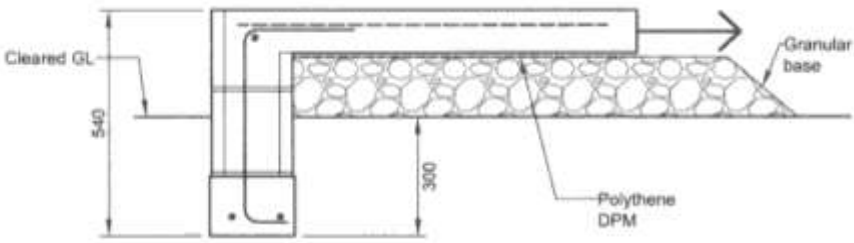


Figure 9. Slab edge specimen 2.

The objective of the tests was to measure the resistance of the edging alone, and minimise the contribution of the slabs. Therefore the slab portions were cast on a double layer of polythene and were not embedded in the basecourse, as shown in the diagrams.

The specimens are scheduled in Table 5.

Configuration	Specimen id	No. of replicates	Imposed load
NZS 3604 in-situ slab edge	1	2	0 kg
			375 kg
NZS 3604 in-situ slab edge, with polystyrene	1a	1	0 kg
			375 kg
NZS 3604 masonry slab edge	2	1	0 kg
			375 kg

Table 5. Slab edge configurations tested.

5.2 Test set-up and procedure

All specimens incorporated attachments at one edge so they could be loaded in the plane of the slab (see Figure 10).

Figure 10. Slab with loadbearing thickening under test.

Applied load was measured with a load cell, and displacements at two corners were measured with potentiometers. All measurements were recorded in text file format for subsequent processing by spreadsheet.

Load was applied to all specimens monotonically. In the case of the slab friction tests, once slipping had initiated, the load was removed, the slabs were left undisturbed for half an hour and the test was repeated.

To simulate imposed load, various concrete blocks were placed on the specimens. For the plain slabs, 375 kg was added, equating to a distributed live load of 1.65 kN/m^2.

For the slab thickening, the imposed load was added in two stages – 690 kg equating to 4.5 kN/m and 1380 kg equating to 9 kN/m. These loads are roughly equivalent to a single-storey and two-storey timber-framed building respectively.

For the slab edge specimens, 375 kg of load was added to simulate a wall load of 2.5 kN/m.

Details are presented in Table 5.

5.3 Observations and results

5.3.1 Floor slabs

Slabs with sand blinding showed behaviour similar to classical sliding friction, with a rapid build-up of resistance then near constant resistance with increasing displacement. The slab without sand blinding showed a more rounded plot shape due to the roughened interface causing interlock. The slabs with thickening had a gradual build-up of resistance as they were forced up the sliding surface. A much lower resistance for the specimen with polystyrene layer shows the ‘bedding in’ effect and compression of the polystyrene.

Representative plots of load resisted against deflection are shown in Figure 11, Figure 12 and Figure 13.

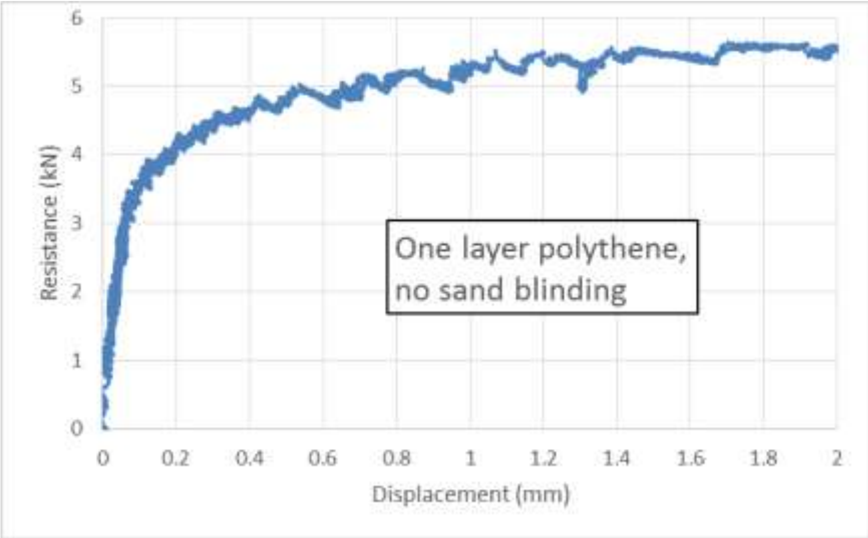


Figure 11. Representative load/displacement plot for slab without sand blinding.

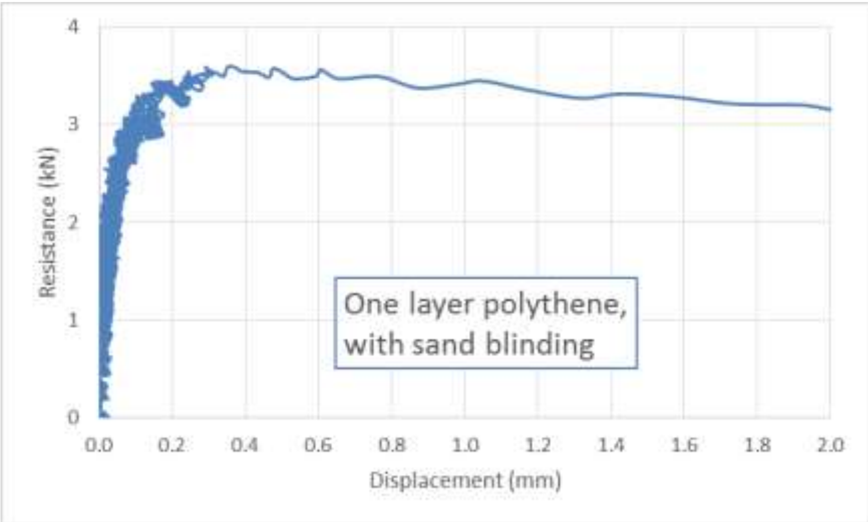


Figure 12. Representative load/displacement plot for slab with sand blinding.

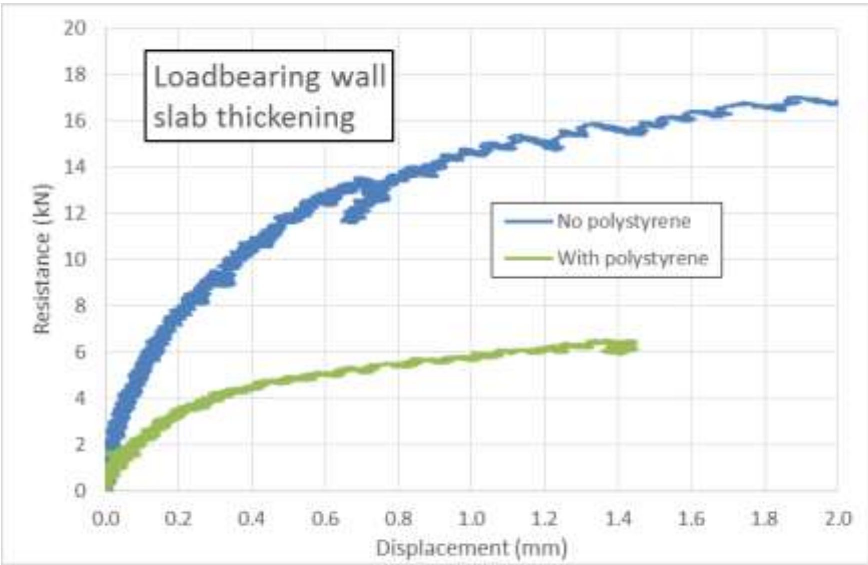


Figure 13. Load/displacement plots for slabs with loadbearing wall thickenings (with and without polystyrene).

5.3.2 Slab edges

All specimens canted up at the outside (foundation) edge because of the eccentricity of load and resistance.

Representative plots of load resisted against deflection are shown in Figure 14, Figure 15 and Figure 16.

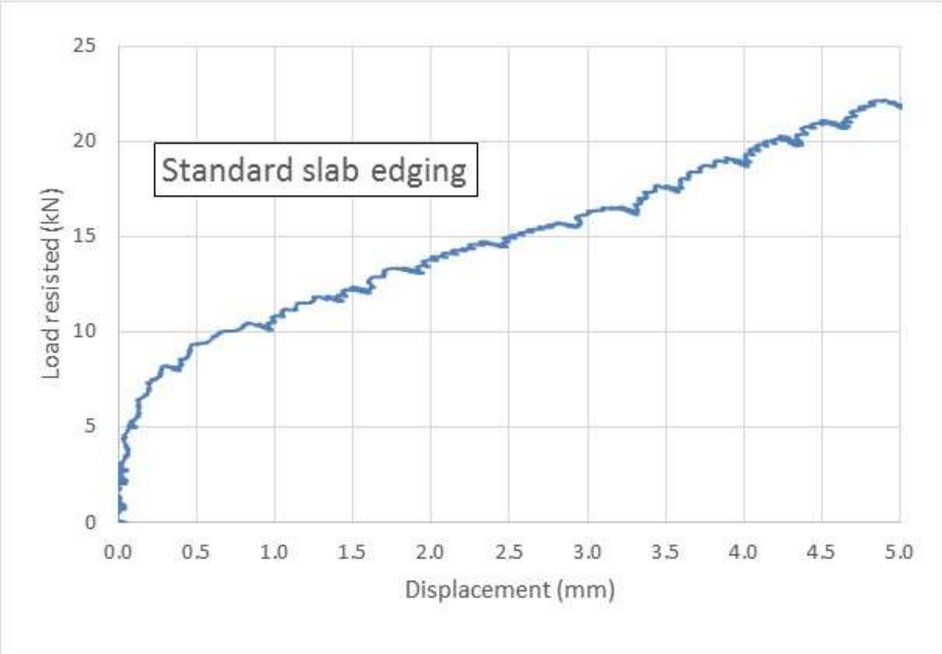


Figure 14. Representative load/displacement plot of standard slab edge.

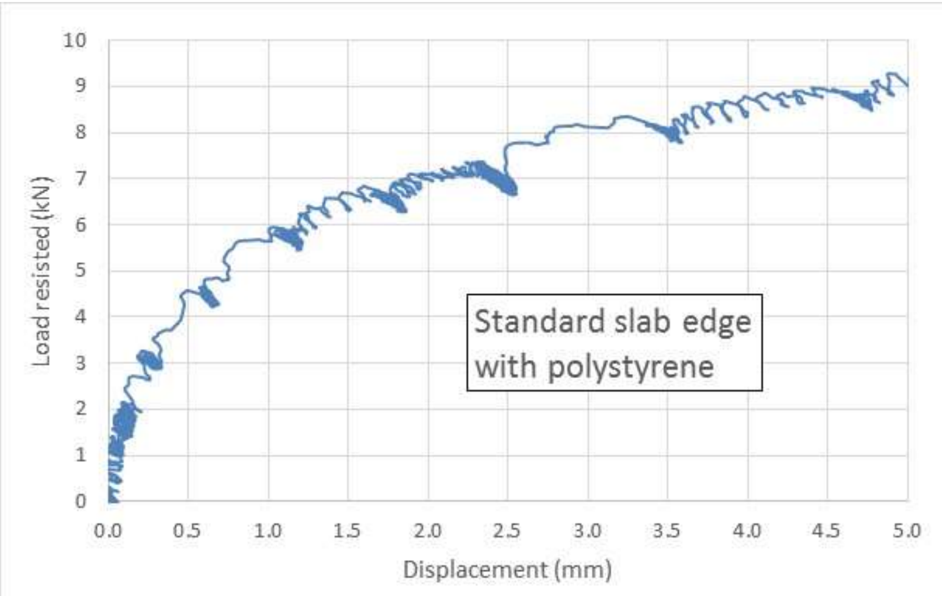


Figure 15. Representative load/displacement plot of slab edge with polystyrene.

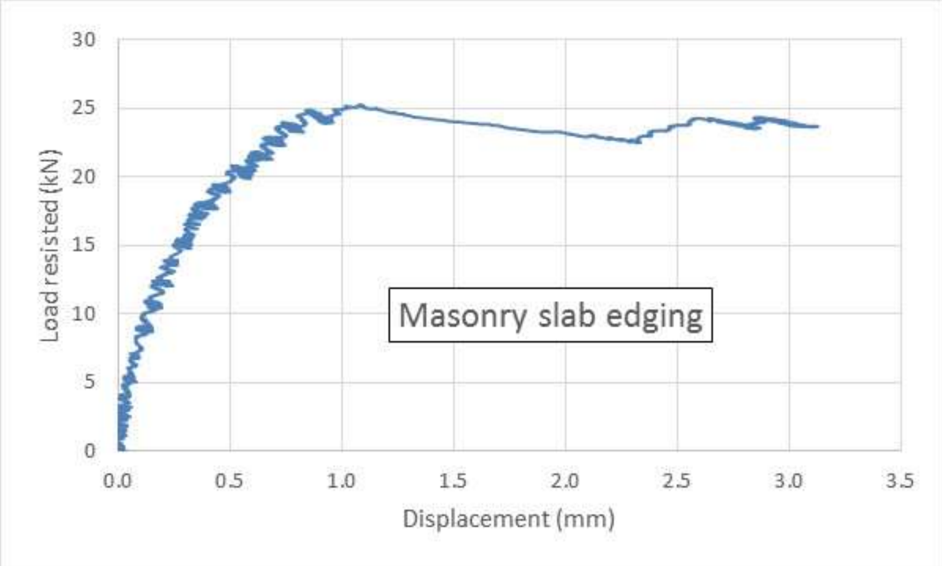


Figure 16. Load/displacement plot of slab with masonry edge.

5.3.3 Numerical results

To characterise the behaviour for the purpose of further analysis, the results were divided into three groups – slabs where friction was the dominant behaviour, other slabs and slab edge foundations.

5.3.3.1 Friction behaviour

The relatively smooth interface of the slabs cast with the polythene laid on sand blinding (specimens 2 and 3) resulted in load/displacement behaviour similar to friction. That is, a steep build-up of resistance with displacement followed by sliding with a constant resistance, independent of displacement.

From a study of the resistance/displacement plots, the point at which sliding began was identified and the load and displacement recorded, together with the maximum load resisted. The coefficient of friction μ was then calculated considering the total gravity load (self-weight and imposed load) acting on the specimen. The results are presented in Table 6.

Configuration	Specimen id.	Test no.	Imposed load (kg)	Sliding begins: Displ (mm)	Sliding begins: Appl load (kN)	Coef. of friction (μ)	Comments
Slab on 1 layer polythene on blinding sand on basecourse	2	1	0	0.25	3.5	0.69	
		2	0	0.25	3.25	0.64	1/2 hr rest
		3	375	0.30	4.7	0.54	
Slab on 1 layer polythene on blinding sand on basecourse	2a	4	0	0.10	3.0	0.59	
		5	0	0.20	3.2	0.63	1/2 hr rest
		6	375	No record file			
Slab on 2 layers polythene on blinding sand on basecourse	3	7	0	0.04	1.5	0.30	
		8	0	0.06	1.65	0.33	1/2 hr rest
		9	375	0.075	2.4	0.27	
Slab on 2 layers polythene on blinding sand on basecourse	3a	10	0	0.02	1.4	0.28	
		11	0	0.08	1.8	0.35	1/2 hr rest
		12	375	0.08	2.55	0.29	

Table 6. Results summary for friction slabs.

5.3.3.2 Non-friction behaviour

The slabs cast without sand blinding and the slabs with a loadbearing wall thickening (specimens 1 and 4) had an uneven interface between slab and basecourse, which provided some interlocking effects and masked the friction effect.

A study of the plots suggested that a bi-linear relationship would be suitable for subsequent analysis. A bi-linear function was superimposed on the plots and the data points manually manipulated to best fit the plot. An example is shown in Figure 17.

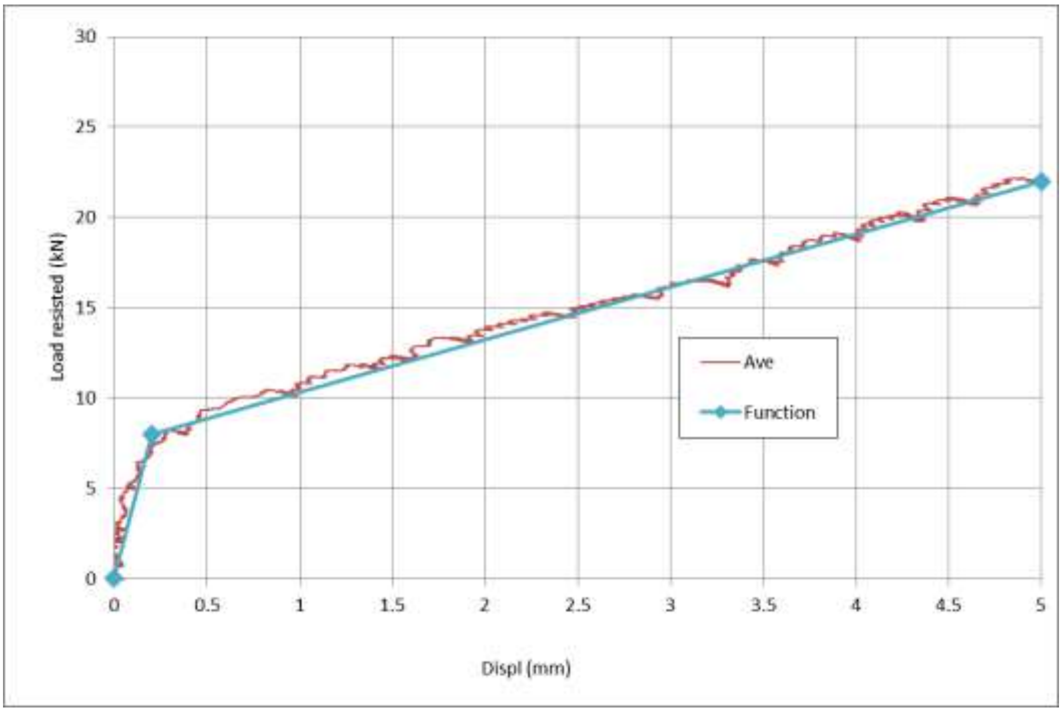


Figure 17. Example best fit function.

Table 7 presents the results of a 'best fit' manual manipulation of the results data plots.

Configuration	Specimen id	Test no.	Imposed load (kg)	Results k1 (kN/mm)	d1 (mm)	k2 (kN/mm)	d2 (mm)	Comments
Slab on 1 layer polythene directly on basecourse	1	1	0	19.5	0.2	0.4	2.1	
		2	0	19.5	0.2	0.2	2.8	After 1/2hr rest
		3	372	15.3	0.4	0.2	5.0	
Slab on 1 layer polythene directly on basecourse	1A	4	0	20.9	0.2	0.5	2.5	
		5	0	17.9	0.3	0.3	2.2	After 1/2hr rest
		6	372	20.5	0.4	0.1	3.3	
Slab with load-bearing wall thickening, on polythene directly on basecourse	4	7	0	28.0	0.2	2.0	2.1	
		8	690	30.0	0.4	2.6	2.6	
		9	1,380	37.5	0.4	4.5	2.4	
Slab with load-bearing wall thickening, on polythene, on polystyrene, on basecourse	4A	10	0	12.0	0.2	0.9	1.8	
		11	690	21.5	0.2	1.6	1.5	
		12	1,380	20.7	0.4	1.3	5.0	

Table 7. Results summary for non-friction slabs.

5.3.3.3 Slab edge foundations

The slab edge load/displacement plots also suggested a bi-linear relationship, and this was done the same way as the non-friction slabs. The results are presented in Table 8.

Configuration	Specimen id	Test no.	Imposed load (kg)	Results k1 (kN/mm)	d1 (mm)	k2 (kN/mm)	d2 (mm)	Comments
NZS 3604 in-situ slab edge	1B	1	0	31.5	0.2	1.5	5.0	
		2	0	27.5	0.2	1.4	5.0	Rest 1/2 hour
		3	372	18.0	0.5	1.8	5.0	
NZS 3604 in-situ slab edge	1A	4	0	31.0	0.2	2.1	4.1	
		5	372	40.0	0.2	4.4	5.0	
NZS 3604 in-situ slab edge, with polystyrene	1a	6	0	22.7	0.2	2.3	1.5	
		7	0	10.0	0.6	0.8	4.7	Rest 2 hours
		8	372	9.7	0.6	0.8	5.0	
NZS 3604 masonry slab edge	2	9	0	46.0	0.6	1.3	3.5	
		10	372	42.5	0.2	7.1	3.5	

Table 8. Results summary for slab edges.

5.4 Conclusions

For analysis purposes, the results of these tests were formulated into equation format, and are plotted in Figure 18.

Friction

Polythene with sand blinding	$\mu = 0.6$	for $\delta > 0.25$ mm.
Polythene without sand blinding	$F = 20\,\delta$	for $\delta < 0.3$ mm,
	$= 6.6 + 0.3(\delta - 0.3)$	$\delta > 0.3$ mm.

Slab edging

Sloping slab edging	$F = 30\,\delta$	for $\delta < 0.2$ mm,
	$= 6 + 1.5(\delta - 0.2)$	$\delta > 0.2$ mm.
Sloping edging with polystyrene	$F = 10\,\delta$	for $\delta < 0.6$ mm,
	$= 6 + 1.2(\delta - 0.6)$	$\delta > 0.6$ mm.
Masonry slab edging	$F = 46\,\delta$	for $\delta < 0.5$ mm,
	$= 23 + 1.25(\delta - 0.5)$	$\delta > 0.5$ mm.

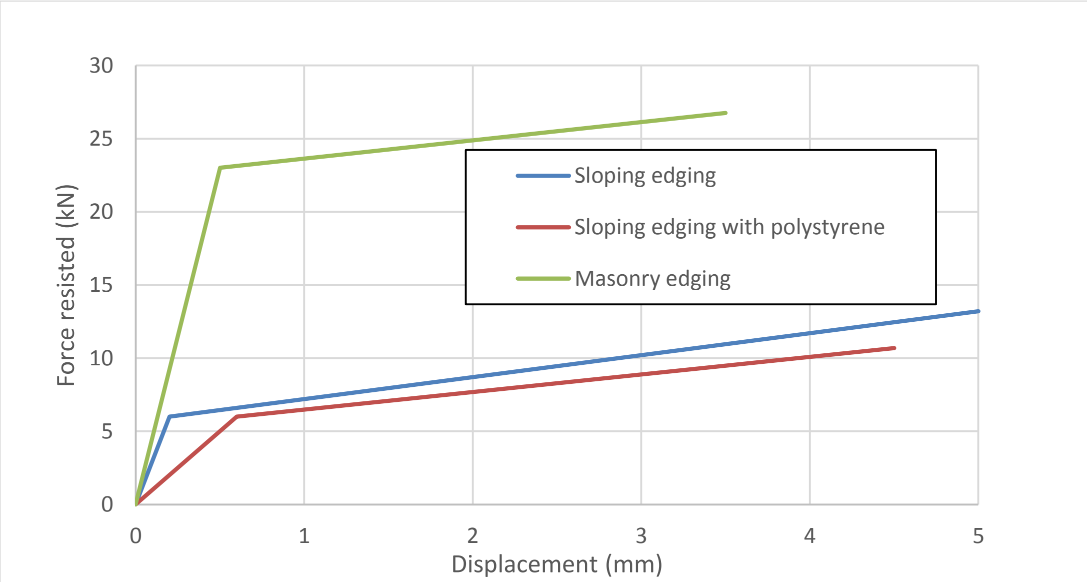


Figure 18. Force/displacement relationships for NZS 3604 slab edging options.

6. SLAB CURLING

Curling of concrete slabs under differential drying shrinkage is described in Walker and Holland (1999) and in ACI 360R-06. Curling occurs when the upper slab surface shrinks at a different rate to the bottom surface. Curling may also occur as a result of differential temperature, but this is not significant for a ground floor slab.

After casting, evaporation of free water to the atmosphere from the top surface of the slab means that moisture loss upwards is much faster than the moisture loss from the bottom surface. This is accentuated for slabs used as floors for internal living spaces because of the damp-proof membrane (DPM) underneath, which is designed to inhibit moisture transfer. The moisture profile through the slab results in a higher shrinkage strain of the top surface and causes the slab to curl upwards at a free edge. This may be the slab edge or a control joint.

Walker and Holland (1999) suggest that concrete stresses due to curling are much more significant than those due to direct shrinkage (1.4–2.8 MPa for curling compared with 0.1–0.4 MPa for direct shrinkage). The direct shrinkage values quoted by them are consistent with the results of the shrinkage analyses described in section 4.3 of this report. To confirm the curling stresses, a non-linear analysis of a representative slab was undertaken.

6.1 Curling analysis

Space Gass structural analysis software was used to construct a model of a floor slab 10 m x 1.0 m x 100 mm thick.

To simulate realistic slab bearing on the foundation, the slab elements were supported on compression only members with spring supports (see Figure 19).

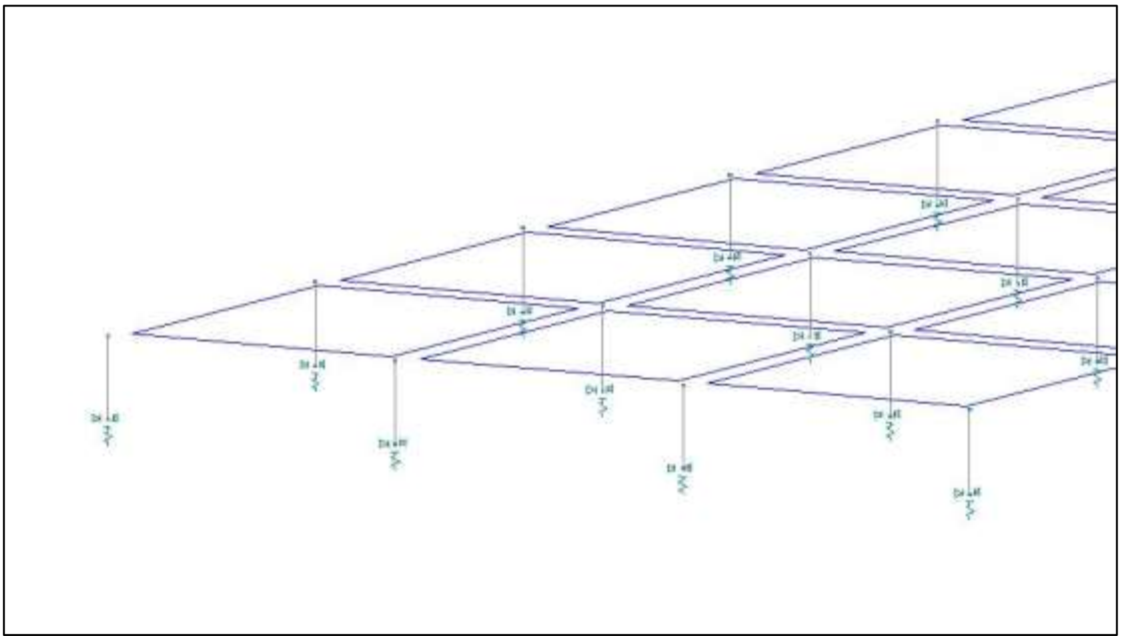
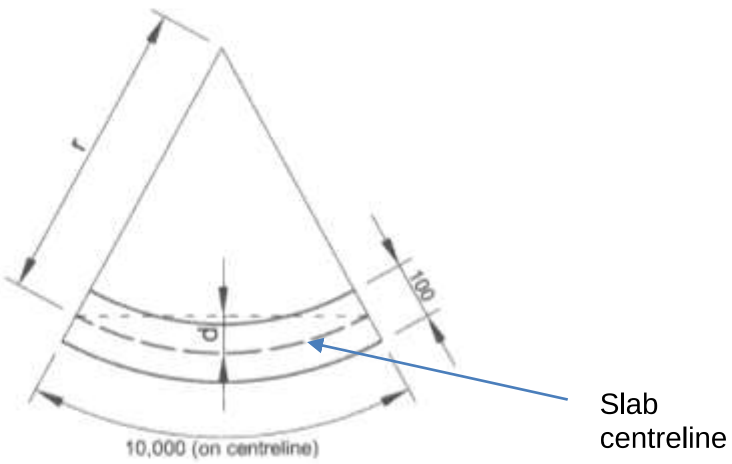


Figure 19. Space Gass model showing plate elements, compression only elements and spring supports.

The spring stiffness was adjusted to represent a range of soil stiffnesses, as quantified by modulus of subgrade reaction, k. The values of k ranged from 5 kPa/mm for loose sand (5,000 kN/m^3) up to 200 kPa/mm for firm rock.

Differential shrinkage strain was modelled using the differential temperature loading feature built in to the software. To calibrate this loading condition, the deflection of the ends of an equivalent slab was calculated under a strain on one surface of 300 μstrain (0.0003 mm/mm):

Radius of curvature r = slab thickness/strain = 100/0.0003 = 333,000 mm.



From geometry:

Deflection d = length^2/(8 x radius) = 10,000^2/(8 x 333,000) = 37.5 mm.

By trial and error, a differential temperature loading of 290° applied to the model gave a deflection of 37.6 mm.

To obtain a measure of the sensitivity of the model, an additional series of analyses was undertaken with the differential shrinkage across the thickness of 0.002 mm/mm. This is a value suggested by Walker and Holland (1999) and The Concrete Society (2003).

The slab was modelled with self-weight loading together with wall weights of 4 kN/m and 10 kN/m. These represent a single-storey building with a medium wall and light roof from NZS 3604, and a heavy wall and roof respectively.

The analysis results are presented in Table 9.

Differential shrinkage strain (μstrain)	**Edge loading**	**Maximum slab stress (MPa) for K_s =**	
		5 kPa/mm	**200 kPa/mm**
200	Zero	2.42	2.35
	Light (4.0 kN/m)	2.50	2.37
	Heavy (10 kN/m)	3.25	2.45
300	Zero	3.65	3.55
	Light (4 kN/m)	3.65	3.57
	Heavy (10 kN/m)	4.13	3.63

Table 9. Results of curl analyses.

The results of this simple example (values ranging from 2.4 MPa to 4.1 MPa) are consistent with the assertion of Walker and Holland (1999). They show that slab curling may be a more significant cause of cracking than direct shrinkage. Assuming the stresses due to direct and differential shrinkage are additive, it can be seen that the likelihood of cracking without mitigating precautions is quite high. Combining typical results from Table 3 and Table 9 gives a concrete stress of between 3 and 4 MPa, compared with a concrete tensile strength of between 1 and 3 MPa.

6.2 Curling tests

Slab curling stresses would be reduced if differential drying shrinkage between top and bottom could be reduced. One possible way to do this would be to introduce a drainage layer under the slab, thus allowing moisture to be lost from both surfaces. To check the feasibility of this, four concrete slabs were cast in a shed at BRANZ. The indoor environment was expected to reduce surface evaporation, thus providing maximum opportunity for the drainage layer to equalise moisture loss and thus the amount of curling.

Two slabs were cast directly on a normal polythene DPM on the concrete floor, and two incorporated a proprietary drainage layer beneath them. Slab surface deflections were measured for 6 weeks.

6.2.1 Test specimens

Four slabs were cast, each 3.0 m x 1.0 m x 100 mm thick, as shown in Figure 20. The relevant details are presented in Table 10.

Figure 20. Slabs ready for casting – specimens D, C, B and A.

Slab	Reinforcement	Base
A	2 – D12 bars	Polythene DPM
B	None	Polythene DPM
C	2 – D12 bars	Drainage layer
D	None	Drainage layer

Table 10. Curl test specimens.

The drainage layer consisted of a proprietary modular drainage system. This consisted of interlocking 30 mm thick cellular plastic grids 1 m x 1 m, together with a 1.2 mm filter fabric on top. The components are shown in Figure 21.

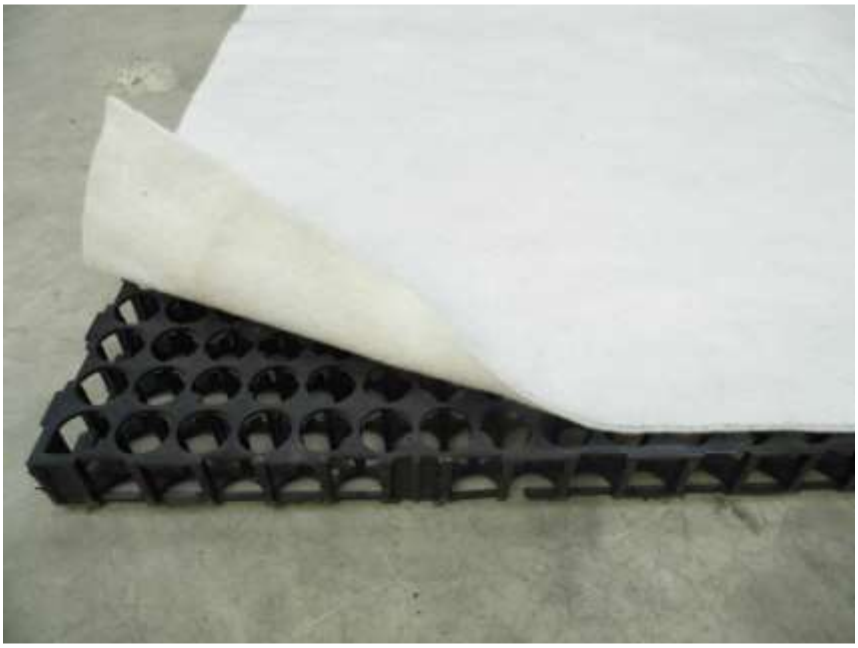


Figure 21. Drainage layer used for the curl tests.

Concrete supplied was a 20 MPa, 130 mm slump, ready-mixed product, with a mix design designated AP2013AW, designed to maximise shrinkage. It was cast into steel moulds laid directly on the concrete floor of the shed and hand trowel finished after casting. No curing compound was used.

6.2.2 Measurements

Slab curl was measured by potentiometers placed at the midpoint and ends of each slab, as shown in Figure 22. The target for each potentiometer was a bolt with a square-faced head set in the wet concrete as shown in Figure 23. The data was recorded by datalogger and stored on a laptop PC at hourly intervals. An uninterruptable power supply was used to guard against power failure.

Figure 22. Slabs with curl-measuring equipment after casting concrete.

Figure 23. Potentiometer target.

6.2.3 Observations and results

Shrinkage movement of each slab could be seen by the break in the laitance at the edges of the moulds.

Deflection readings at slab centres showed embedment of approximately 0.2–0.4 mm for slabs A and B and 0.7–0.9 mm for C and D, reflecting the softer base for the latter.

Net curl (deflection of the slab centre from a notional line joining the ends) after 20 days and 6 weeks is shown in Table 11.

Slab	Curl at 20 days (mm)	Curl at 42 days (mm)
A (polythene DPM)	1.78	3.25
B (polythene DPM)	1.65	3.2
C (drainage layer)	1.75	3.0
D (drainage layer)	2.1	4.15

Table 11. Curling tests results summary.

Clearly, the drainage layers have not reduced the magnitude of the curl. In fact, the highest result was slab D with a drainage layer. On dismantling the specimens, there was no evidence of any water in the drainage layer, indicating that the majority of the mixing water loss occurred through the top of the slab, just as for the normal slab.

6.2.4 Conclusion

The drainage layer was not successful in reducing slab curling because moisture loss from the top surface was still much greater than moisture loss through the drainage layer from the bottom surface.

7. CONCLUSIONS

Overall conclusions from this project:

- Practical concrete mixes used for floor slabs contain more water than is required for hydration of the cement. This water must be lost from the slab before it can be used as a habitable floor. Moisture loss results in shrinkage of the concrete during the drying process.
- Floor slabs incorporating typical foundation details provide restraint to the shrinkage of the slab. This results in a build-up of internal stresses during the initial curing period when concrete strength is not fully developed. The use of polystyrene insulation on the sloping surface of the typical slab edge thickening does reduce this effect.
- Moisture loss upwards by evaporation is much greater than loss downwards, which is additionally inhibited by the presence of the DPM. Therefore, differential shrinkage occurs through the thickness of the slab, which gives rise to upwards curling, particularly at the edges.
- Analysis showed that slab stresses due to curling are likely to be considerably higher than those due to direct shrinkage, and the combined tensile stresses are similar to the concrete tensile strength. Therefore, precautions need to be taken during construction to avoid concrete cracking.
- Typical codes of practice (for example NZS 3604 and various good-practice guides) outline these precautions, which include:
    - care with mix design and curing
    - addition of shrinkage reinforcing to encourage fine, distributed cracking
    - limiting the length of the slab between shrinkage control joints.
- Testing of typical slab details showed that the resistance between slab and ground is:
    - slab on polythene DPM on sand blinding, friction coefficient $\mu = 0.6$.
    - masonry slab edging, $F = 46\,\delta$ for $\delta < 0.5$ mm,
$= 23 + 1.25(\delta - 0.5)$ $\delta > 0.5$ mm.
    - sloping slab edging, $F = 30\,\delta$ for $\delta < 0.2$ mm,
$= 6 + 1.5(\delta - 0.2)$ $\delta > 0.2$ mm.
    - sloping slab edge with polystyrene, $F = 10\,\delta$ for $\delta < 0.6$ mm,
$= 6 + 1.2(\delta - 0.6)$ $\delta > 0.6$ mm.

    (slab edge forces per metre width)
- Reduction of slab curling due to differential moisture gradient is not likely to be significantly reduced by the addition of a simple drainage layer beneath the slab.
- Reduction of slab shrinkage by other means such as proprietary systems was not investigated because it was outside the scope of the project as contracted by the Building Research Levy.

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