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Measurements of Shrinkage and Creep Strains on Post tensioned Waffle Slab

Mesures du retrait et fluage dans une dalle en caissons précontraintes

Messungen der Schwind- und Kriechdehnungen einer nachgespannten Rippendecke

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Introduction

In 1966 a post tensioned waffle slab was constructed for the Council of the City of Sydney. During construction and since the slab has been in service as a parking station, a detailed investigation has been carried out into the behaviour of the structure, and in particular a large series of measurements were made of shrinkage and creep strains.

Description of Structure

The maximum overall dimensions of the suspended concrete deck were 259'-0" x 191'-6" and as it was essential that large vehicles have easy access underneath, it was decided to locate the columns on a grid 58'-0" x 57'-4" with one span 62'-0" and with cantilevers 10'-0", 12'-0" and 13'-0".

The maximum live load used in the elastic analysis of the suspended slab was taken as 60 lbs. per square foot, which was equivalent to the whole area of the slab being completely covered with the heaviest vehicles which were likely to use it. However, under the most likely parking layout for this slab the uniformly distributed live load will be about 25 lbs. per square foot and it was decided that a loading of 30 lbs. per square foot would be taken as the live load when making calculations for load balancing.

For the ultimate analysis of the slab, the maximum possible load was taken to be a live load of 100 lbs. per square foot which was equivalent to 2000 people in each bay.

The suspended slab consists of a waffle slab of total depth 15" which includes a top flange 3" deep. The ribs of the waffle slab are 6" wide and 12" deep at 2'-6" centres in both directions. Over the inverted cone-type precast concrete capital there is a bottom flange to the waffle slab which is also 3" thick. A plan of the slab is shown in Fig.1.

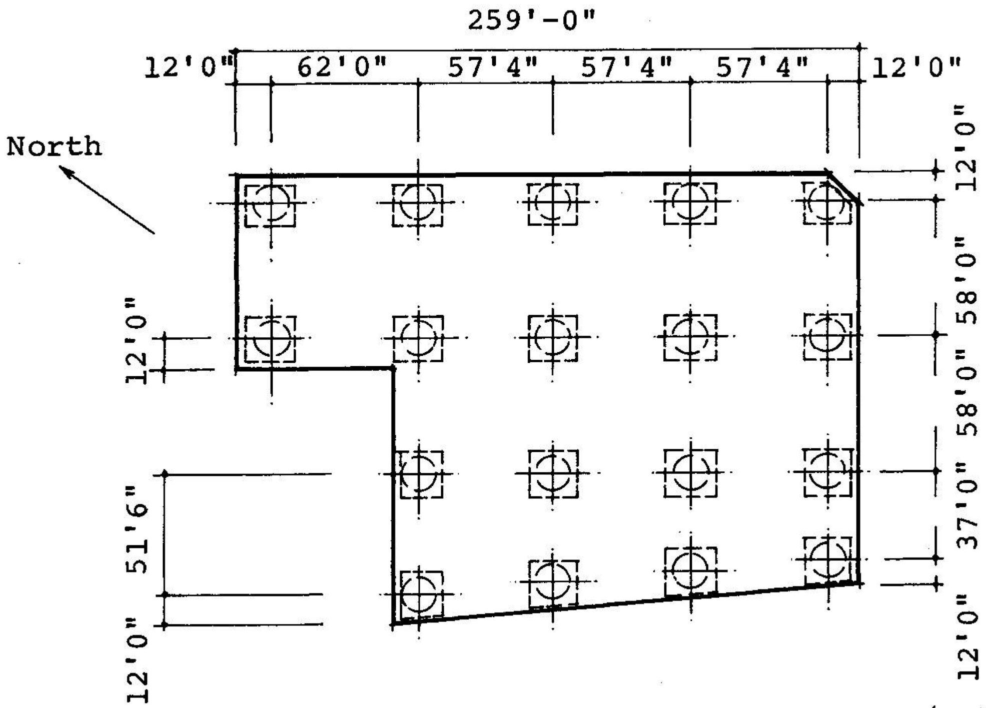

FIG.1 PLAN OF DECK AND COLUMN GRID LAYOUT

The slab is post tensioned with four ½" diameter stress relieved strands in each rib and thus the tendons are equally spaced in both directions. The four ½" diameter strands pass through oval shaped galvanised steel ducts 2½" x 3/4" which were filled with grout after the post tensioning. The amount of prestress in each tendon is identical, but the distance of the centre of the tendon from the neutral axis of the concrete section was varied from rib to rib and throughout the length of the tendon in order that the average prestressing force in the tendon would approximately balance the dead load of the slab plus a live load of 30 lbs. per square foot on the slab. In general, the strands were stressed from both ends and were continuous throughout the full length and breadth of the slab.

Welded wire fabric was used to reinforce the upper flange of the waffle slab and the lower flange where it occurs over the columns, and in addition, over each column in the top of the slab there are ½" diameter cold worked deformed bars at 3" centres in both directions. The only other reinforcement in the slab is steel reinforcement stirrups in the ribs in areas surrounding the column supports.

The column Capitals consist of precast cones which are separated from the slab by teflon and neoprene bearing pads. These cones are 16'-0" in diameter with a total depth of 4'-0" and the cones together with the waffle slab are shown in Fig. 2. The columns consist of 24" diameter reinforced concrete poured in precast concrete pipes 1-5/8" thick, and the columns are supported on pile caps which rest on groups of piles to bedrock.

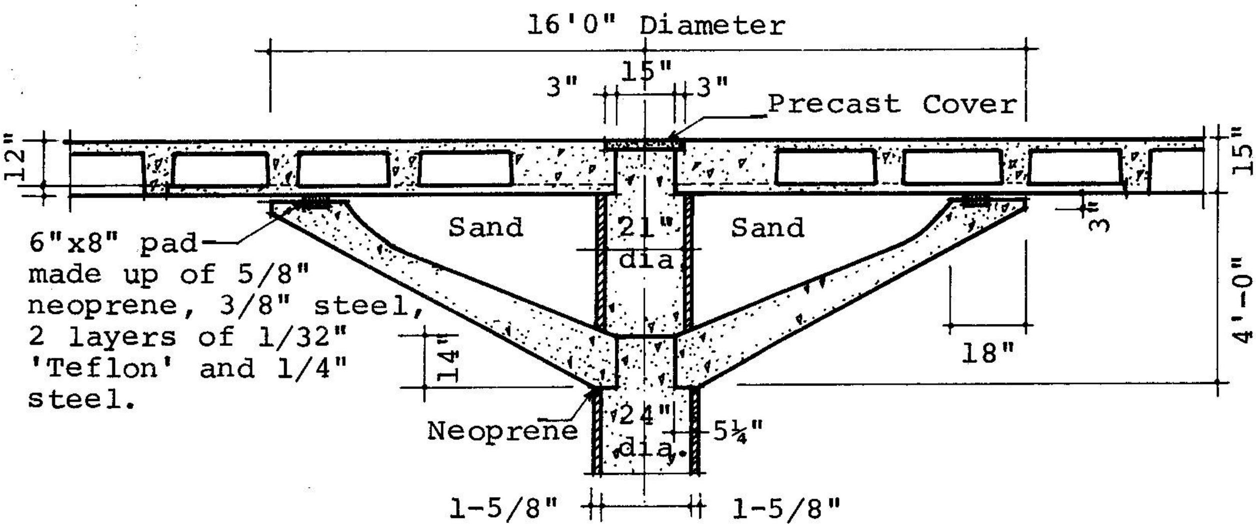

FIG.2 SECTION THROUGH WAFFLE SLAB AND COLUMN CAPITAL

Under dead load and a live load of 30 lbs. per square foot, the average concrete compression stress was 765 lbs. per square inch except over the column heads where it was 530 lbs. per square inch, in both cases after the assumed losses have taken place. The elastic stresses under dead load with live load of 60 lbs. per square foot comply with the provisions of the relevant Code, and there is a load factor of two against flexural failure under dead load plus a live load of 100 lbs. per square foot. The principal tensile stresses were checked under the combined action of prestress, flexure and shear. With a load factor of 1.8 and a live load of

60 lbs. per square foot, the maximum tensile stress at the critical section for shear was 188 lbs. per square inch, acting at an angle of 62 degrees to the neutral axis.

As no control joints were provided in the slab, construction joints were made so as to divide the slab into 5 pours, each of approximately 200 cu.yds. and a sixth pour was made of the access bridge to the main slab. The same aggregate, brand of cement, water cement ratio and mix proportion were used for each of the six pours, but as shown later, it is believed that different batches of cement which were ground to a varying degree of fineness resulted in a variation of concrete strength and shrinkage between different pours. The concrete was specified to have a compressive strength of 4000 lbs. p.s.i. in 28-day cylinders and it was specified that there should be a minimum increase in cylinder strength after one year of 25%. The total shrinkage was specified as not more than 500×10^{-6} in laboratory shrinkage tests on standard (A.S.T.M.) prisms. Curing consisted of an initial sprayed curing compound followed by a continuously water sprayed hessian covering. The curing continued until stressing commenced 25 days after placing of concrete.

Testing

The following tests were carried out -

(1) Laboratory tests on cylinders at 7 days, 14 days, 28 days, 100 days and 1 year.

(2) Laboratory shrinkage tests on 3"x3"x11" prisms.

(3) Field shrinkage tests on 3"x3"x11" prisms.placed at top of the slab.

(4) Field measurements of strain in the prestressed slab, using vibrating wire strain gauges.

(5) Measurement of actual contraction of the slab at its edges from brass plugs embedded in the slab.

(6) Measurement of deflection of the slab from about 50 brass plugs embedded in surface of the slab and measured by optical methods.

(7) Measurement of bending moments over column heads by strain gauges attached to reinforcement in slab.

(8) Measurement of strain, using a vibrating strain gauge in an unstressed concrete waffle slab 5 ft. long x 3 ft. wide, which has been placed on the main slab.

(9) Measurement of temperature within the body of the slab.

(10) Laboratory tests on the elastic modulus of concrete at various ages.

Results of Compressive and Shrinkage Tests

Table 1. Compressive strengths in 12"x6" cylinders in p.s.i.

POUR NO.	Age at Test				
	7 Days	14 Days	28 Days	100 Days	12 Months
1	2886	3796	3755	4280	4140
2	3548	3836	4383	4166	5026
3	3482	4028	4572	5010	5770
4	3344	3902	4343	4910	5400
5	3240	3946	4128	4470	5470
6	3402	4044	4419	4804	5290

Table 1 shows the average compressive strengths from cylinders at various ages. In the case of the cylinders taken at 28 days there were 24 cylinders taken in each of the six pours. For pour No.1 the average was 3,755 p.s.i. with a standard deviation of 435 p.s.i. for the 24 cylinders. For the average of the other five pours the mean was 4,368 p.s.i. for 120 cylinders. It can be shown that the difference of 613 p.s.i. between these two means is highly significant. Similarly, the average for pour No.3 at 28 days was 4,572 p.s.i. with a standard deviation of 241 p.s.i. for 24 cylinders. The difference between this mean and the mean for the other five pours, 4,204 p.s.i., is also statistically highly significant. In both cases the significance level is less than 0.2%. For this reason separate curves for development of compressive strength were plotted for pours 1, 3 and the remainder of the pours and these are shown in Fig.3.

Table 2 gives the results of 36 laboratory shrinkage specimens. These were cured for 18 hours in a humidity room at a relative humidity of 90% or above, and then immersed for 27 days in limewater. The specimens were then stored in a drying room in accordance with an A.S.T.M. Standardisation Procedure C157. From Table 2 can be seen that the shrinkage of the six specimens taken from pour No.1 appears to be rather less than the shrinkage of the specimens taken from the other five pours. Using the Wilcoxon's Sum of Ranks Test, it was shown

Table 2 Laboratory Shrinkage Specimens Strain x 10^{-6}

SPEC-IMEN NO.	POUR NO.	28 Days	32 Days	35 Days	42 Days	56 Days	84 Days	91 Days	104 Days	117 Days	140 Days	252 Days	476 Days
97	1	17	187	257	313	440	524			439	452	482	462
99	1	-184	-40	36	91	241	336			335	328	373	315
101	1	-107	96	164	187	290	425			420	392	424	325
103	1	-101	68	133	234	329	484			436	425	485	445
105	1	-67	79	167	240	363	488			465	449	508	469
107	1	-100	70	162	244	392	492			470	450	495	471
109	2	-108	103	123	248	327	384		467		440	451	472
111	2	-71	142	162	271	387	463		517		522	559	525
113	2	-82	174	187	295	413	485		528		537	618	567
115	2	-88	128	147	261	366	449		509		515	547	499
117	2	-115	97	126	237	326	422		457		458	517	486
119	2	-73	132	144	221	346	421		444		439	493	438
121	3	-68	135	173	275	382	439		481		472	524	504
123	3	-133	54	106	221	354	409		470		451	498	479
125	3	-80	104	148	227	327	377		432		424	441	411
127	3	-90	112	177	262	382	438		506		499	560	537
129	3	-104	109	149	284	366	416		487		474	527	508
131	3	-89	116	171	271	388	439		501		492	544	521
133	4	-96	130	169	241	376	428		481		482	509	549
135	4	-141	111	150	232	370	420		480		500	546	540
137	4	-107	112	147	226	353	403		452		472	507	495
139	4	-86	138	182	254	386	430		481		495	551	538
141	4	-122	90	140	201	333	371		398		423	451	408
143	4	-79	140	192	262	418	455		479		485	538	512
145	5	-91	142	184	273	370	412		429		451	454	447
147	5	-85	111	159	250	377	446		479		479	489	469
149	5	-83	139	179	295	419	503		539		556	581	587
151	5	-60	158	200	300	414	489		528		518	556	560
153	5	-104	118	149	271	415	483		498		488	551	529
155	5	-149	69	102	208	321	391		425		426	450	436
157	6	-136	27	107	220	344	409	424			484	563	512
159	6	-67	121	192	315	438	492	517			584	648	589
161	6	-75	92	162	279	429	475	500			559	628	570
163	6	-106	47	115	232	353	408	433			476	572	491
165	6	-214	-17	63	190	325	364	386			429	505	475
167	6	-135	48	114	233	378	428	443			474	535	464

that the difference was highly significant. Therefore the results of the laboratory shrinkage for pour No.1 are shown separate from pours 2 to 6 in Fig.4.

It can be seen from a comparison of figures 3 and 4 that the concrete with the lower compressive strength had lower shrinkage. The average compressive strength of pour 1 at 12 months was 16% less than the other pours while at the same age the shrinkage from pour 1 specimens was about 14% less than the others.

Table 3 shows the results of the 36 sets of field shrinkage prisms. These were cured for 18 hours in a humidity room and then taken onto the site and given the same curing and treatment as the concrete slab. It is noticable that the strain for the field shrinkage specimens at 42 days was about one half the strain of the laboratory shrinkage specimens but at 252 days the field shrinkage is less than one third of the laboratory shrinkage. Also there is variation in field shrinkage with the position of the specimen on the parking deck. Further, the field shrinkage was affected by daily and seasonal variations in temperature and humidity.

Table 3 Field Shrinkage Specimens Strain x 10^{-6}

SPECIMEN NO.	POUR NO.	28 Days	35 Days	42 Days	56 Days	70 Days	84 Days	105 Days	140 Days	175 Days	252 Days	336 Days	420 Days	504 Days
98	1	42	195	-34	63	140	194	188	110	105	138	247	130	136
100	1	89	190	-6	82	68	115	101	60	63	81	179	55	48
102	1	89	148	-9	61	118	151	141	93	89	102	213	108	103
104	1	74	153	-23	42	125	174	190	158	135	145	230	127	86
106	1	6	126	-80	-5	41	98	125	93	68	102	195	57	65
108	1	92	170	-34	69	126	189	197	139	141	145	229	131	94
110	2	140	-18	88	219	71	166	285	30	200	105	120	262	188
112	2	101	-52	40	188	27	120	224	-10	130	66	88	206	149
114	2	111	-40	71	199	40	146	262	6	199	89	107	246	202
116	2	169	-16	109	237	86	158	274	8	181	106	103	218	179
118	2	179	12	126	240	93	200	325	63	261	177	183	322	291
120	2	99	-48	73	182	102	141	223	4	184	114	114	223	192
122	3	110	-15	124	201	79	152	265	20	207	165	163	265	179
124	3	164	30	172	206	87	236	262	29	178	153	152	287	174
126	3	85	-32	98	153	43	108	226	-7	170	124	97	229	114
128	3	64	-21	131	195	69	179	284	38	219	162	146	287	180
130	3	72	-8	134	193	70	171	255	21	184	163	139	285	148
132	3	60	-10	130	187	31	117	251	-30	116	79	66	219	101
134	4	1	191	97	115	198	146	238	116	186	178	216	151	309
136	4	27	92	108	124	176	124	207	119	179	171	177	112	301
138	4	21	90	108	119	186	141	231	121	182	139	156	100	281
140	4	38	121	140	173	221	164	203	158	220	205	213	141	324
142	4	-30	75	87	117	175	125	201	95	161	113	115	65	230
144	4	-10	71	85	119	199	137	209	106	186	169	190	136	301
146	5	-22	148	258	115	205	140	100	127	224	156	172	135	296
148	5	-28	121	225	91	184	124	84	107	158	141	152	121	256
150	5	-24	131	228	116	187	135	115	128	148	127	148	98	265
152	5	-3	150	214	116	202	141	110	129	190	178	188	154	305
154	5	7	161	247	149	223	176	136	141	186	150	170	119	260
156	5	-14	108	183	76	152	68	32	118	150	120	120	50	219
158	6	93	190	156	62	165	383	89	156	63	184	202	182	73
160	6	161	214	230	101	229	391	133	159	91	279	148	227	130
162	6	101	183	168	69	174	372	118	119	68	189	189	168	70
164	6	101	175	181	54	164	334	80	119	62	202	182	181	95
166	6	91	202	179	67	135	369	79	79	6	129	113	100	-6
168	6	131	218	176	81	189	380	111	133	81	201	191	177	108

Negative strains denote expansion of the specimens.

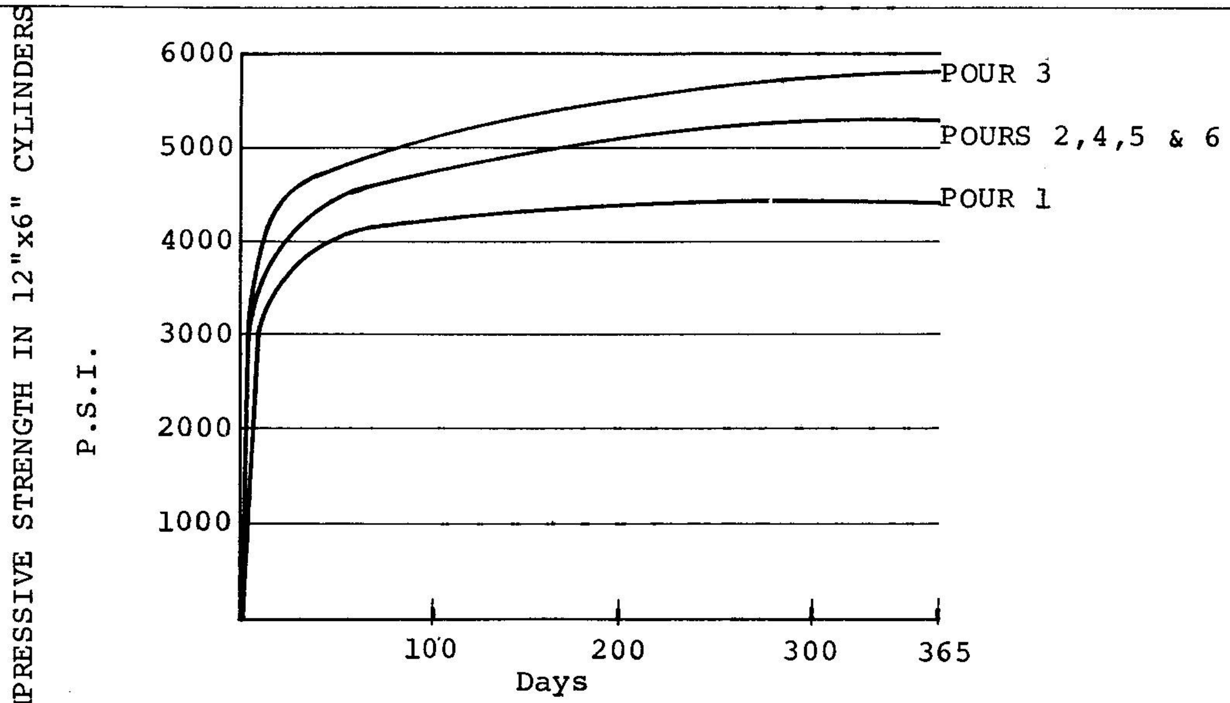

FIG.3 DEVELOPMENT OF COMPRESSIVE STRENGTH WITH AGE

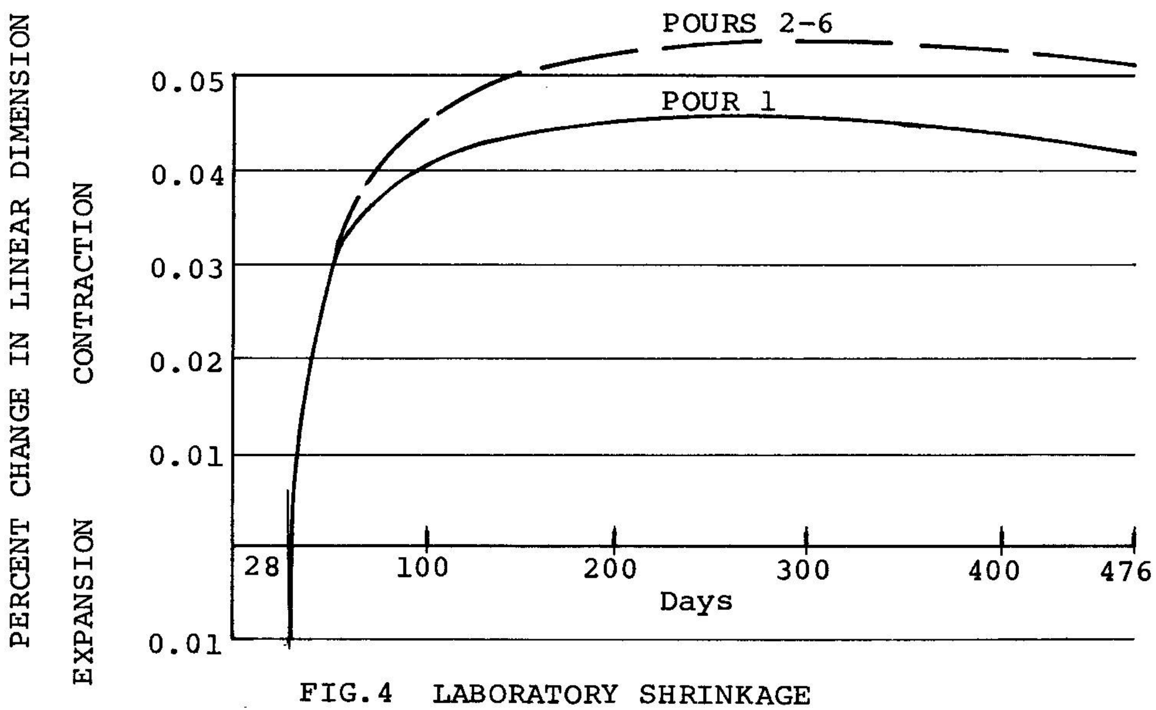

FIG.4 LABORATORY SHRINKAGE

Results from Vibrating Strain Gauges

The vibrating strain gauges were set into blocks of concrete approximately 3"x3"x5" on the day before the slab was poured and the block was then supported within the legs of large bar chairs which also supported the tendon ducts. Of the 44 gauges used, all except 3 gave results which could be compared with the strains measured from the shortening of the slab. Naturally, there was considerable unexplained variation between one gauge and another and it was apparent that to obtain reasonable results, a considerable number of gauges must be used.

In general, the concrete showed an initial expansion which occurred for at least one week after the pouring of the concrete. The expansion varied between 50 x 10^{-6} and 170 x 10^{-6} and at the time of stressing the concrete was still in an expanded condition. The post tensioning caused an average contraction of 140 x 10^{-6} and a further contraction due to creep and shrinkage of 190 x 10^{-6} occurred in the 3 months after prestressing. In the following 21 months an additional contraction of 150 x 10^{-6} took place. On a gauged line of 259 ft. the total measured contraction 2 years after the initial post tensioning of the concrete was 1½" which corresponds to a strain of 480 x 10^{-6} . Fig. 5 shows the average strain using results both from vibrating strain gauges and measurements from brass plugs embedded in the slab.

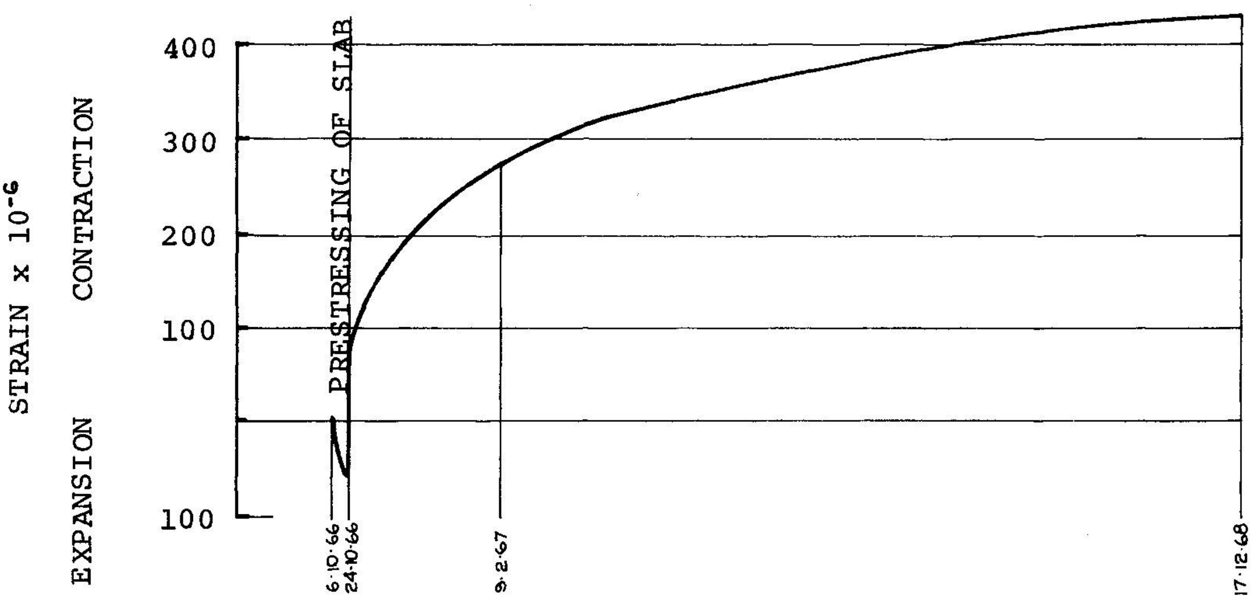

FIG.5 MEASURED STRAINS ALONG GRID LINE B

The gauge in the block which was not stressed, showed an expansion strain of 40 x 10^{-6} 21 days after pouring of the concrete. Contraction due to shrinkage then occurred so that 23 months later the measured strain was 170 x 10^{-6} . The result obtained by the vibrating wire strain gauge on the unstressed block was in agreement with the results on the field shrinkage prisms.

Acknowledgement

The Division of Building Research, C.S.I.R.O. and the Engineering Department of the Council of the City of Sydney carried out the detailed measurements of the structure during construction and in service. The Cement and Concrete Association of Australia made funds available to assist the C.S.I.R.O. in carrying out its share of the work.

SUMMARY

Results are presented of laboratory and field measurements of strains due to prestressing, creep and shrinkage in a post tensioned waffle slab. Prior to prestressing the concrete showed an initial expansion of about 100×10^{-6}. In the unstressed specimens the expansion turned to shrinkage after about 21 days with a contraction after 23 months of 170×10^{-6}. Measurements of the stressed slab showed a total shrinkage plus creep contraction of 340×10^{-6}. Measurements of shrinkage in the laboratory gave results more than twice those in the field.

RESUME

On présente des résultats de mesures effectuées en laboratoire et au chantier des dilatations provoquées par la précontrainte, le fluage et le retrait d'une dalle en caissons. Avant la précontrainte, le béton indiquait un allongement d'environ 100×10^{-6}. Pour le spécimen non-précontraint, l'allongement est devenu une contraction après environ 21 jours avec une contraction après 23 mois de 170×10^{-6}. Les mesures de la dalle précontrainte ont indiqué un retrait plus fluage total de 340×10^{-6}. Les mesures du retrait en laboratoire ont donné des résultats deux fois plus grand que celles sur l'ouvrage en place.

ZUSAMMENFASSUNG

Es werden die Ergebnisse von Dehnungsmessungen in Labor und Feld mitgeteilt, die sich aus Vorspannung, Kriechen und Schwinden in einer nachgespannten Rippendecke ergaben. Vor der Nachspannung wies der Beton eine Quellung von ungefähr 100×10^{-6} auf. In den unbelasteten Probestücken verwandelte sich das Quellen nach etwa 21 Tagen in Schwinden mit einem Schwund von rund 170×10^{-6} nach 23 Monaten. Messungen an der belasteten Decke zeigten einen totalen Schwund samt Kriechen von 340×10^{-6}. Schwindmessungen im Labor ergaben doppelt so hohe Werte wie jene im Feld.