PREDICTION OF STRENGTH DEVELOPMENT IN CONCRETE STRUCTURES

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Early removal of side forms from concrete members may cause mechnical damage or lead to frost damage. Currently, achievement of a cube compressive strength of 5 N/mm^2 is the criterion for avoiding such damage, but recent research indicates that the value may be reduced to 2 N/mm^2. Soffit forms may be removed when members have sufficient flexural strength to withstand self-weight of the concrete and other applied loads. In addition, deflections must not be excessive. Research has shown that the proportion of design load applied at early age should not exceed the proportion of design compressive strength achieved at that age in the member under consideration. The relationships between compressive strength and two parameters, maturity equivalent and equivalent age, are discussed. Equivalent age is shown to be useful for the prediction of strength from a known temperature history at early age when the compressive strength development is very sensitive to curing temperature. At later ages, maturity equivalent may be more suitable for prediction purposes. A method of prediction of temperature history in hydrating concrete members has been combined with these methods of prediction of compressive strength to determine the times at which formwork may be removed, based on the criteria described.

•THE material cost of the formwork is a substantial part of the overall cost of a reinforced concrete structure. In addition, delays in its reuse may lead to late completion of the structure and increased on-site costs. Considerable economy may therefore be achieved by removing the formwork from a structural member and reusing it as soon as possible.

The criteria for striking formwork depend on whether the formwork is used vertically or horizontally, that is, as side forms or soffit forms. Side forms are only required to contain the concrete until such time as it is self-supporting. Thereafter, they may be removed subject to avoiding damage in the process of removal and damage caused by freezing of immature concrete in adverse weather conditions. Soffit forms, however, must remain in place until the structural member is capable of carrying its self-weight and any applied construction loads without risk of collapse or excessive deflection.

The criteria for these situations, as discussed in this paper, may be related to the development of the compressive strength of the concrete. This, in itself, depends primarily on the concrete mix proportions and its temperature history. The latter is, of course, determined by a number of factors including the dimensions of the structural member, the thermal insulation value of the formwork, the ambient temperature, the placing temperature of the concrete, and the cement type and content.

A method of temperature prediction that considers these parameters is available. Provided that a suitable means can be found to relate the compressive strength of concrete to its temperature history, the compressive strength development in a structural member and hence formwork striking times may be predicted.

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Frost Damage

A number of researchers have reported that freezing concrete at early age may lead to a considerable loss of potential strength. Möller (1) summarized earlier work and conducted his own experiments to determine at what age concrete is no longer susceptible to frost damage (as distinct from freeze-thaw damage). Both he and Powers (2) concluded that the required ages for concrete of various design strengths may be conveniently related to the achievement of a given compressive strength. This conclusion seems to have been the basis of various specification clauses. For example, the British Code of Practice CP110 specifies that the temperature of concrete is unlikely to be damaged when it has reached a cylinder strength of 3.4 N/mm^2. Considering the correlation factor between cube and cylinder strengths, these two criteria are in fairly close agreement.

A point that must be emphasized is that these strength criteria are not indicative of the ability of concrete to resist tensile forces created by the expansion that takes place during the phase change of water to ice. They are related, as Powers (2) has suggested, to a reduction in free water and the creation of pore space to accommodate ice as it forms.

Sadgrove (3) has reexamined the strength criterion by determining the loss of strength that occurs at 28 days and 91 days as a result of early freezing. He concluded that minimal loss of strength would prevail if the concrete had achieved a cube strength of 2 N/mm^2 before freezing. This lower strength criterion may permit a modest reduction in striking times.

Mechanical Damage

Before the work by Harrison (7), there seems to have been no experimental work reported on this subject; an unsupported recommendation is given elsewhere (5). Harrison examined the damage caused by early striking of formwork to the surfaces and arrises of concrete prisms. He concluded that the risk of damage was slight provided that the concrete had achieved a cube strength of 2 N/mm^2 for all but the very high-strength mixes. For the latter, a minimum curing period was necessary. These recommendations assumed that reasonable care was taken in removing the formwork. Subsequent mechanical damage caused, for example, by site plant cannot be avoided by a strength criterion; physical means of protection must be used.

Dead and Imposed Loading

Loads applied to beams or slabs at early age may cause failure through crushing of the concrete or inadequate bond. Alternatively, the loads may be adequately supported but give rise to excessive deflections. In determining the proportion of load that may be applied at early age, Sadgrove studied the development of bond strength (6) and the structural strength and deflection characteristics of beams loaded at early age (7).

From theoretical considerations, the ultimate moment of a balanced section, at any age up to 28 days, should be directly proportional to the compressive strength of the concrete at that age as shown in Figure 1 (1), and an underreinforced section will develop flexural strength more rapidly at early ages. This has been confirmed experimentally (7). Bond strength was also found to develop more rapidly than compressive strength at early age (6). Thus it was shown that bond was unlikely to be a limiting criterion for early loading if the assumption is made that all sections are balanced.

The shrinkage, elastic, and creep deflections at early age were measured (7). The shrinkage deflection was independent of the age at which drying began. Elastic and creep coefficients were much greater at early age. However, the limitation on the load that can be applied at early age and the rapid decrease in the coefficients with

Figure 1. Development of ultimate moment of resistance, bond strength, and compressive strength.

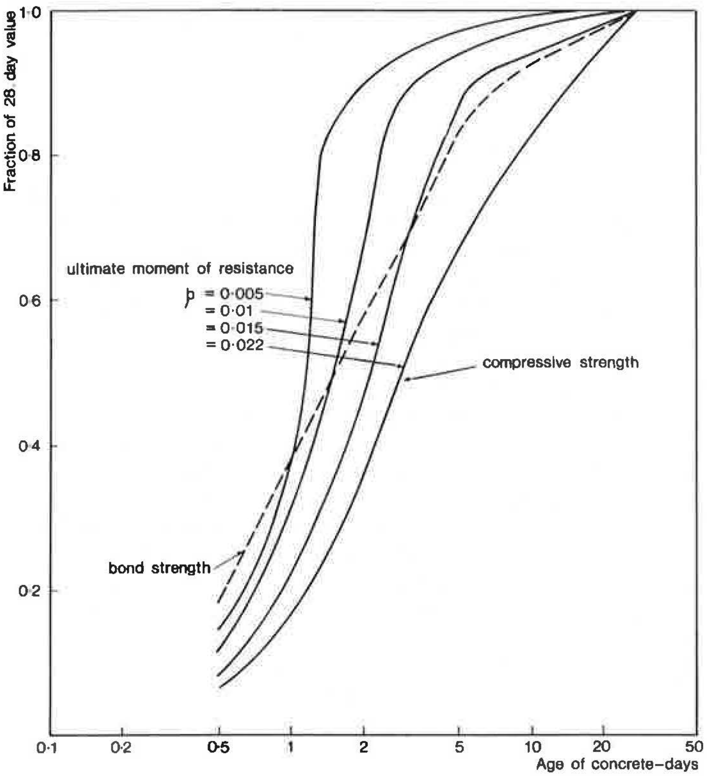
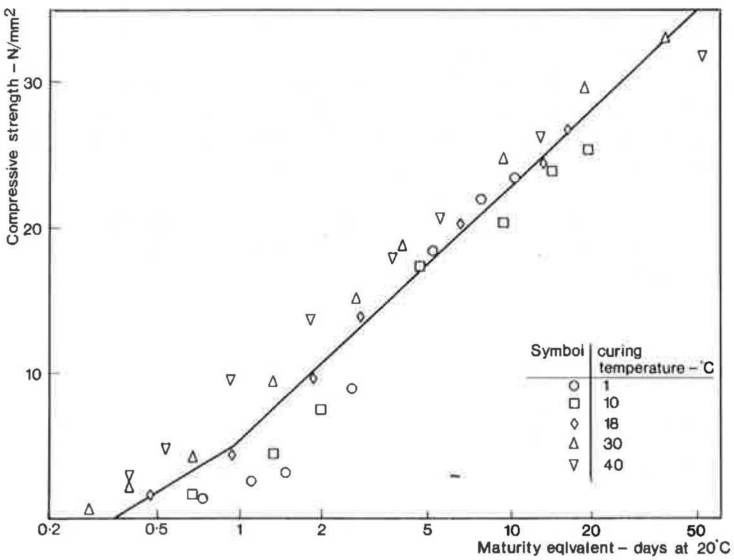


Figure 2. Compressive strength versus maturity equivalent.



increasing age effectively caused no significant increase in the deflections that might be anticipated at later age with normal loading patterns.

The final conclusion is that the proportion of full working load that may be applied to a structural member at early age is equal to the proportion of the design strength of the concrete achieved at that age.

DEVELOPMENT OF COMPRESSIVE STRENGTH

A number of researchers (10, 11, 12, 13) have proposed that there is a relationship between the compressive strength of concrete and maturity that is defined as $\Sigma(\theta + 10)\Delta t$, where θ = temperature of the concrete at any time and Δt = increment of time.

It is postulated that samples of the same concrete having equal maturities will have equal compressive strengths, regardless of their temperature histories. The results from various series of tests on the compressive strength of concretes cured over a range of temperatures have, in general, validated this hypothesis, but most of the results considered have related to fairly mature concrete. Results have been reported by Sadgrove (7) on concrete cured at constant temperature in the range of 1 to 45 C and tested in compression at ages of 5 hours to 28 days. When the compressive strength values from these tests were plotted against maturity, it was found that, although there was quite a good relationship for comparatively mature concrete, there was considerable scatter at low values of maturity. This is shown in Figure 2, where compressive strength is plotted against maturity equivalent, that is, simply maturity divided by 30 C and expressed as days at 20 C. Examination of the pattern of the results at low maturity equivalent indicated that compressive strength is initially more sensitive to changes in curing temperature than maturity suggests. A trial and error method was therefore used to determine the factor related to temperature by which actual age is related to age at 20 C. The factor finally proposed is

$$F = \left[\frac{\theta + 16}{36}\right]^2 \qquad (1)$$

where θ is not less than -10 C.

The sum of the products of this factor and increments of time, that is, $\Sigma F \Delta t$, is called equivalent age and is expressed in days at 20 C.

The values of compressive strength shown in Figure 2 are replotted against equivalent age in Figure 3. Much better agreement is now evident at strengths up to about 15 N/mm^2, and agreement beyond this level is fairly good. However, a given error in equivalent age gives a larger difference in actual time than the same error in maturity equivalent because the former depends on a second-order equation of temperature. Equivalent age therefore appears to be most suitable as a parameter for the prediction of strength at early age; maturity (or maturity equivalent) may be more appropriate at later age (an arbitrary division might be made at 3 days equivalent age).

PREDICTION OF TEMPERATURE HISTORY

Weaver (12) has developed a method of predicting the temperature history of a hydrating concrete element with a constant ambient temperature based on biaxial heat flow. For a solution of the heat flow equation, values for the following are required:

1. Placing temperature of the concrete,
2. Ambient temperature,
3. Section dimensions,
4. Boundary conductances,
5. Thermal conductivity of the concrete,

Figure 3. Compressive strength versus equivalent age.

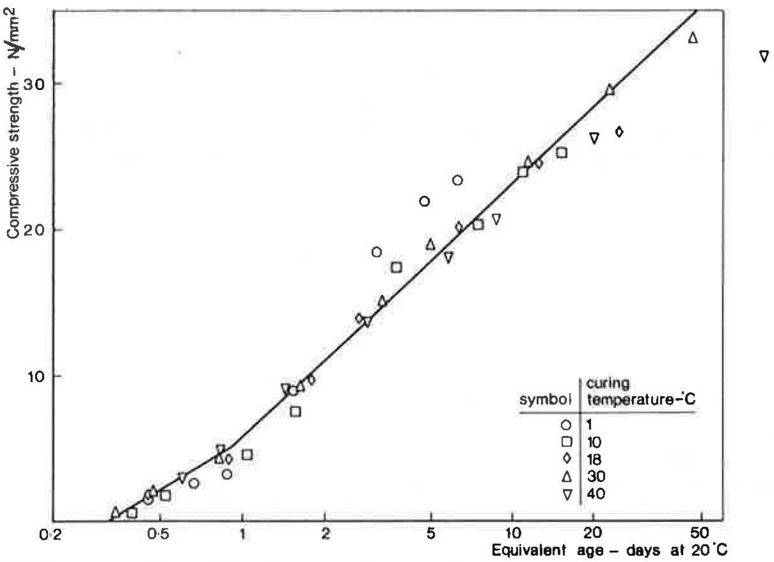


Table 1. Striking times of portland cement concrete with 330-kg/m³ cement content and 22.5-N/mm² characteristic strength.

Formwork Conductance (W/m² deg C)	Ambient Temperature (C)	Resistance to Damage (N/mm²)	Characteristic Strength Reached	
			33 Percent	66 Percent
18.9	-5	—[a]	—[a]	—[a]
	0	155	245	—[b]
	5	88	140	476
	10	60	93	309
	15	42	66	219
10.0	-5	—[a]	—[a]	—[a]
	0	140	230	—[b]
	5	80	132	464
	10	54	87	303
	15	39	60	213
6.5	-5	—[a]	—[a]	—[a]
	0	120	208	—[b]
	5	69	120	447
	10	48	78	292
	15	36	56	206
5.0	-5	—[a]	—[a]	—[a]
	0	105	192	—[b]
	5	62	110	434
	10	44	72	282
	15	35	53	199
3.4	-5	—[a]	—[a]	—[a]
	0	81	156	—[b]
	5	52	90	404
	10	40	62	261
	15	33	48	183
2.0	-5	68	156	—[b]
	0	48	81	570
	5	40	60	316
	10	35	50	201
	15	32	43	142
1.3	-5	48	76	—[b]
	0	42	60	429
	5	36	52	238
	10	34	47	163
	15	32	43	127

[a]Concrete is frozen before it reaches D level of 5 N/mm².
[b]Strength level is not reached before 1,000 hours.

6. Specific heat of the concrete,
7. Density of the concrete,
8. Thermal diffusivity of the concrete,
9. Cement content, and
10. Heat evolved by the cement in a given time increment.

The latter value may be predicted from data giving the total heat evolved at any time at a reference temperature and by using the time-temperature equation proposed by Rastrup (13):

$$\tau_r = 2^{\gamma(\theta - \theta_r)} \cdot t \tag{2}$$

where

θ = reaction temperature (here assumed constant),
θ_r = reference temperature,
t = time (from start of hydration),
τ_r = equivalent time at reference temperature, and
γ = reciprocal of the increase in temperature that doubles the rate of hydration.

The value of γ may be determined from the slope of the lines relating logarithm of time to evolve given total quantities of heat to the difference between reaction and reference temperatures. Thus heat evolution data are also needed at temperatures other than the reference temperature.

PREDICTION OF STRIKING TIMES

A computer program has been written, based on the method derived by Weaver (12), that predicts the temperature at the arris of a hydrating concrete element at given time intervals. The temperature at the arris is the lowest that is likely to occur within the element, and strength prediction based on the temperature at this point will therefore be conservative. The equivalent age increment of each time interval is calculated, and the total equivalent age is determined. This value is then compared with the equivalent age required for a given concrete to achieve various levels of compressive strength. When the required equivalent age is reached, the actual age is tabulated. Thus a series of striking times have been produced (14).

In addition to the values required for the temperature prediction as given in the previous section, the program must have input data relating to the concrete design strength and the strength levels for which times are predicted. The first set of tables uses design cube strengths of 22.5, 30, and 37.5 N/mm^2 because the tables were produced to conform with the draft Code of Practice (15). A revision is envisaged that would conform with the characteristic strengths specified in CP110, that is, 20, 25, 30 and 40 N/mm^2. The strength levels are D, 33 percent, and 66 percent, as given in Tables 1, 2, 3, 4, 5, and 6 (15). The placing temperature is 10 C. D indicates the level at which concrete is unlikely to suffer frost or mechanical damage, for which a strength of 5 N/mm^2 is used; the second and third levels are percentages of the characteristic strength. In the revised tables, 2 N/mm^2 would be used for the first level, and a fourth level equal to 100 percent of design strength may be introduced. However, for the 66 and 100 percent levels, the parameter maturity equivalent would probably be used in the prediction rather than equivalent age in view of the previous discussion.

A version of the striking times tables relating to current United States practice is being prepared. The units are in the U.S. customary system, and American Concrete Institute standards are used where relevant. Because of the wider range of ambient temperatures prevailing in the United States, the ranges have been selected as appropriate to the form type. For instance, very low ambient temperatures are only considered where high insulation values are used.

Table 2. Striking times of portland cement concrete with 380-kg/m³ cement content and 22.5-N/mm² characteristic strength.

Formwork Conductance (W/m^2 deg C)	Ambient Temperature (C)	Resistance to Damage (N/mm^2)	Characteristic Strength Reached: 33 Percent	Characteristic Strength Reached: 66 Percent
18.9	-5	—[a]	—[a]	—[a]
	0	150	240	—[b]
	5	88	140	472
	10	57	93	309
	15	42	63	219
10.0	-5	—[a]	—[a]	—[a]
	0	135	225	—[b]
	5	80	128	460
	10	51	84	300
	15	36	60	210
6.5	-5	—[a]	—[a]	—[a]
	0	116	204	—[b]
	5	66	114	441
	10	44	74	286
	15	34	52	202
5.0	-5	—[a]	—[a]	—[a]
	0	99	183	—[b]
	5	58	104	426
	10	41	67	276
	15	32	49	194
3.4	-5	—[a]	—[a]	—[a]
	0	72	144	—[b]
	5	48	82	392
	10	37	57	250
	15	31	44	174
2.0	-5	56	116	—[b]
	0	42	69	525
	5	36	52	286
	10	33	45	179
	15	29	39	125
1.3	-5	40	64	—[b]
	0	36	51	357
	5	34	46	196
	10	31	42	138
	15	29	38	110

[a]Concrete is frozen before it reaches D level of 5 N/mm².
[b]Strength level is not reached before 1,000 hours.

Table 3. Striking times of portland cement concrete with 380-kg/m³ cement content and 30.0-N/mm² characteristic strength.

Formwork Conductance (W/m^2 deg C)	Ambient Temperature (C)	Resistance to Damage (N/mm^2)	Characteristic Strength Reached: 33 Percent	Characteristic Strength Reached: 66 Percent
18.9	-5	—[a]	—[a]	—[a]
	0	115	240	—[b]
	5	64	140	452
	10	42	93	297
	15	30	63	210
10.0	-5	—[a]	—[a]	—[a]
	0	100	225	—[b]
	5	56	128	440
	10	36	84	285
	15	27	60	201
6.5	-5	—[a]	—[a]	—[a]
	0	80	204	—[b]
	5	48	114	420
	10	34	74	274
	15	26	52	192
5.0	-5	—[a]	—[a]	—[a]
	0	66	183	—[b]
	5	42	104	406
	10	32	67	262
	15	26	49	184
3.4	-5	—[a]	—[a]	—[a]
	0	51	144	657
	5	36	82	370
	10	30	57	237
	15	25	44	165
2.0	-5	40	116	—[b]
	0	36	69	489
	5	30	52	266
	10	27	45	167
	15	25	39	118
1.3	-5	32	64	—[b]
	0	30	51	321
	5	28	46	180
	10	26	42	129
	15	25	38	104

[a]Concrete is frozen before it reaches D level of 5 N/mm².
[b]Strength level is not reached before 1,000 hours.

Table 4. Striking times of portland cement concrete with 450-kg/m^3 cement content and 30.0-N/mm^2 characteristic strength.

Formwork Conductance (W/m^2 deg C)	Ambient Temperature (C)	Resistance to Damage (N/mm^2)	Characteristic Strength Reached	
			33 Percent	66 Percent
18.9	-5	—[a]	—[a]	—[a]
	0	110	240	—[b]
	5	64	140	452
	10	42	90	294
	15	30	63	207
10.0	-5	—[a]	—[a]	—[a]
	0	95	220	—[b]
	5	52	124	436
	10	36	81	282
	15	27	57	198
6.5	-5	—[a]	—[a]	—[a]
	0	72	196	—[b]
	5	42	108	414
	10	30	68	266
	15	24	48	186
5.0	-5	—[a]	—[a]	—[a]
	0	57	171	—[b]
	5	38	94	394
	10	29	60	253
	15	24	44	176
3.4	-5	—[a]	—[a]	—[a]
	0	42	123	633
	5	32	70	352
	10	27	49	222
	15	23	39	152
2.0	-5	36	76	—[b]
	0	30	54	420
	5	28	44	218
	10	25	38	133
	15	23	34	95
1.3	-5	28	48	576
	0	27	42	213
	5	26	40	130
	10	24	36	101
	15	23	33	85

[a]Concrete is frozen before it reaches D level of 5 N/mm^2.
[b]Strength level is not reached before 1,000 hours.

Table 5. Striking times of portland cement concrete with 450-kg/m^3 cement content and 37.5-N/mm^2 characteristic strength.

Formwork Conductance (W/m^2 deg C)	Ambient Temperature (C)	Resistance to Damage (N/mm^2)	Characteristic Strength Reached	
			33 Percent	66 Percent
18.9	-5	—[a]	—[a]	—[a]
	0	85	200	—[b]
	5	52	116	432
	10	33	75	282
	15	24	54	198
10.0	-5	—[a]	—[a]	—[a]
	0	70	180	—[b]
	5	40	104	416
	10	27	66	270
	15	21	45	189
6.5	-5	—[a]	—[a]	—[a]
	0	52	156	—[b]
	5	33	87	396
	10	24	56	256
	15	20	40	178
5.0	-5	—[a]	—[a]	—[a]
	0	42	132	663
	5	30	74	376
	10	24	49	242
	15	20	37	168
3.4	-5	52	220	—[b]
	0	33	90	600
	5	28	56	334
	10	23	41	211
	15	20	34	144
2.0	-5	32	60	—[b]
	0	27	45	393
	5	24	38	202
	10	22	34	124
	15	21	31	90
1.3	-5	24	44	512
	0	24	39	189
	5	22	34	120
	10	21	32	95
	15	20	30	81

[a]Concrete is frozen before it reaches D level of 5 N/mm^2.
[b]Strength level is not reached before 1,000 hours.

Table 6. Striking times of portland cement concrete with 490-kg/m³ cement content and 37.5-N/mm² characteristic strength.

Formwork Conductance (W/m² deg C)	Ambient Temperature (C)	Resistance to Damage (N/mm²)	Characteristic Strength Reached: 33 Percent	Characteristic Strength Reached: 66 Percent
18.9	-5	—[a]	—[a]	—[a]
	0	85	200	—[b]
	5	48	116	432
	10	33	75	282
	15	21	51	198
10.0	-5	—[a]	—[a]	—[a]
	0	70	180	—[b]
	5	40	100	416
	10	27	63	270
	15	21	45	189
6.5	-5	—[a]	—[a]	—[a]
	0	52	152	—[b]
	5	33	84	390
	10	24	52	252
	15	20	38	176
5.0	-5	—[a]	—[a]	—[a]
	0	39	126	654
	5	28	68	370
	10	23	45	236
	15	19	34	164
3.4	-5	48	200	—[b]
	0	33	81	585
	5	26	50	322
	10	22	38	201
	15	20	31	136
2.0	-5	28	52	—[b]
	0	24	42	345
	5	22	36	170
	10	21	32	105
	15	20	29	78
1.3	-5	24	40	356
	0	21	36	141
	5	22	32	100
	10	20	30	83
	15	19	28	72

[a]Concrete is frozen before it reaches D level of 5 N/mm².
[b]Strength level is not reached before 1,000 hours.

CONCLUSIONS

1. Methods of relating the compressive strength of concrete to time and temperature have been combined with a method of temperature prediction in hydrating concrete elements to predict the times at which certain levels of strength are reached in the elements.

2. The times at which both side and soffit forms may be removed from a concrete element can conveniently be related to the strength achieved in the element.

ACKNOWLEDGMENTS

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