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EFFECT OF COLD WEATHER ON CONCRETE STRENGTH AND DURABILITY

1. Background

The effect of cold weather on concrete strength and durability is an issue that surfaced recently on one of our projects where the night time ambient temperature fell to -4ºC, i.e. below the specified lower threshold of 5ºC. In this instance the surface temperature of the LCS dropped to 1ºC, but the minimum internal temperature of the concrete stayed above 7ºC on the five non-conforming Lots of the work.

Core testing indicated that the concrete 7 day strength was already above the minimum requirement of 5 MPa, but the Client did not accept the concrete and required that proof should be provided that the concrete durability was not compromised. This was later redefined as their concern about the resistance to erodability of the surface layer of the LCS. In the absence of such proof, it was stated that the Principal requires the concrete to be removed and replaced. This disposition is not provided by the Specification.

I did a lot of research and wrote a very detailed technical paper: "Report on Subbase Concrete Placed Outside the Specified Temperature Limits".

2. Purpose

The purpose of this PIN is to summarise the issues and problems related to defining and testing for durability, resistance to abrasion and erodability, as a handy reference in case it is required in the future.

3. Specification Requirements

Clause 4.3.4	-	Concrete must not be placed at **shade temperatures** <5ºC or >36ºC;
	-	Concrete temperature at discharge must be >10ºC or <32ºC;
	-	If diurnal air temperature changes are >/= 20ºC, the upper limit for concrete shall be 30ºC;
Clause 4.3.8.1	-	Must undertake continuous surface temperature monitoring for the first 24 hours after placement to ensure that the temperature of the concrete does not fall below 5ºC;

- Failure to maintain the temperature of the concrete at or above 5ºC will constitute a non-conformance.

Comments:

1. *There is no mention what the disposition is or should be;*
2. *Presumably Corrective Action is intended;*
3. *There is no mention of the required action in the Specification Section 5 – End Product Criteria.*

Clause 5.3.4 - Concrete must achieve an in-situ compressive strength of 5 MPa within 42 days;

- Subbase which fails to achieve an in-situ compressive strength of 4 MPa within 42 days must be removed and replaced.

Comments:

1. *In the Specification for End Product Criteria, conformance to strength only is required;*
2. *Nowhere in the Specification is there a definition or mention of "durability".*

4. Required Concrete Attributes

- Total binder: min 90 kg/m^3 cement + min 160 kg/m^3 flyash.
- Compressive Strength:5 MPa in 42 days
- Slump: 20 – 40 mm:
- Drying shrinkage: <550 μm
- Entrained air: 5.0% +/- 2%

5 Cold Weather Concreting

Since 1990, various researchers have quite clearly demonstrated the technical feasibility of using chemical additives to depress the freezing point of mixing water and to accelerate the setting of concrete. It has been shown that using certain cold weather admixture systems the temperature of the concrete can be allowed to drop to as low as -5ºC after mixing, without any detrimental effects to the end product.

To convince the industry professionals to adjust their thinking and because of the increasing need to place concrete under conditions where freezing temperatures were expected prior to significant strength gain having been achieved, an ASTM C 1622 "Standard Specification for Cold Weather Admixture Systems" has now been issued.

This specification is based on commercial chemical admixtures that either depress the freezing point or accelerate the hydration rate of the cement. It not only covers temperatures down to -5ºC, but also stipulates allowable ranges for slump and air content (Ref 5).

Ref 4 postulates that concreting down to -5ºC temperatures will become the norm under the national Standard and with the evolvement of dedicated admixtures, concrete curing temperatures to -10ºCwill become reality.

Comment:
Issuing the ASTM Standard would infer that cold weather concreting is allowable, provided certain precautions are taken.

6. Definition of Durability

The term "durability" too often has a meaning as it appears "in the eyes of the beholder". This is because it does not have a succinct definition, nor are there a defined criteria or tests for these.

It has been postulated that durability involves the assessment of the following:

- Physical durability – Resistance to frost (freeze/thaw) actions ("D"cracking);
  - Thermal properties of aggregate and cement paste;
  - Abrasion resistance
- Mechanical durability
- Chemical durability

This, of course, covers a wide range of attributes which may also be conflicting. In particular job specific specifications, job specific durability requirements should not only be stated, but also the method of testing nominated and the actual results required.

No definitions for durability are provided by the RTA Specification, RTA Concrete Pavement Manual, Austroads Pavement Design Guide or the RTA Draft Supplements to the latter, nor the QDMR Pavement Design Manual. The American Concrete Institute offers the definition as: "The ability of concrete to resist weathering action, chemical attack, abrasion and other conditions of service". This is still unsatisfactory as it is quite subjective and all embracing and the last phrase can mean anything an individual wishes to include.

7. Expert Assessment of Correlation with Durability

The following extracts from various references are provided to illustrate the problem of attempting to define the generic term "durability". These are self explanatory:

7.1 Ref 8 p.368: "For **plain concrete** the requirements of durability for different exposures are given in terms of the free water/cement ratio, the minimum cement content and the strength. The reason for specifying minimum cement content and strength is that the water/cement content is not easy to measure and control for compliance purposes."

7.2 Ref 8 p.327; "… properties such as **mix proportions, density, air content and workability** have to comply with specifications so as to satisfy both strength and durability requirements".

7.3 Ref 9 p.99: "**Physical durability** of aggregates refers to soundness and wear resistance. …. Wear resistance of aggregates plays some part in wear resistance of concrete under traffic, particularly in areas where studded tyres are allowed."

7.4 Ref 8 p.170: "If concrete that has **not yet set is allowed to freeze**, the mixing water converts to ice and there is an increase in the overall volume of the concrete. Since there is now no water available for chemical reactions, the setting and hardening of the concrete are delayed and consequently there is little cement paste that can be disrupted by the formation of ice. When at a later stage thawing takes place, the concrete will set and harden in its expanded state, so that it will contain a large volume of pores and consequently have a low strength."

7.5 Ref 8 p.171: "If freezing occurs **after the concrete has set**, but before it has developed an appreciable strength, the expansion associated with the formation of ice causes disruption and irreparable loss of strength."

7.6 Ref 8 p.171: "If however the concrete has acquired a sufficient strength before freezing, it can withstand the internal pressure generated by the formation of ice from the remaining mixing water…… Generally, the more advanced the hydration of the cement and the **higher the strength of concrete, the less vulnerable it is to frost damage.**

7.7 Ref 12 Cl 3.2: "**Durability of the surface of the concrete pavement can be expected to improve with the compressive strength of the concrete in the surface layer".**

7.8 Ref 15: A very detailed study for "Extending the Season for Concrete Construction and Repair" was carried out by the US Corps of Engineers in 2003/4. This involved laboratory testing and five full scale field experiments. Their findings (p47) in relation to this paper were:

- **Admixtures do not reduce the freeze/thaw durability** of concrete, and
- If the concrete starts out at a temperature of at least 10ºC and stays above 0ºC for at least 6 hours, it will be able to resist frost damage for one temperature excursion to -20ºC (concrete temperature.

Comment:
In summary, the expert opinion appears to be that the degree of durability correlates to the strength of concrete. If, however, one looks at abrasion resistance in isolation, then this will not be true in all circumstances.

8. Discussion on Issues Relating to Abrasion

A simple definition would be that abrasion relates to the resistance to wear of a (concrete) surface. In contrast with the other durability related concrete properties, abrasion resistance is considered to be a mechanical property.

Depending on the size of the particle(s) and its motion relative to the concrete surface, as well as on the properties of the aggregates and its fracture, abrasion is initiated either in the hydrated cement paste matrix, in the aggregates or in the paste-aggregate interface. In such a process it is obvious that close correlation should exist between abrasion resistance and other mechanical properties of the concrete, such as the compressive or tensile strength, provided they are representative of the properties of the near surface regions exposed to abrasion (Ref 11).

The main problem in defining concrete resistance to abrasion is the choice (or absence) of suitable test methods (Ref 11 – 7.3.3a). ASTM offers a number of options from shot blast or sand blast methods to Vickers and Brinell hardness and even microhardness to evaluate concrete surface resistance to abrasion. In all instances there are no meaningful objective results, as all measure the mortar strength (which would be very different from, say, the Brinell hardness of an aggregate particle).

There are some interesting findings from the 1921 Duff A Abrams research on concrete properties on some 10,000 specimens. Most of these are regarded as valid today. The following are worth noting:

- Experiments showed the strong influence on abrasion resistance of water/cement ratio, the duration of curing and the grading of aggregates;
- Wear decreased with decreasing w/c ratio;
- Wear decreased with increased duration of curing;
- Wear decreased with the reduction of the sand content in the mix;
- Abrasion was more pronounced on wet specimens compared to dry ones;
- Variations in the above parameters reflected themselves both in abrasion resistance and concrete compressive strength;
- Evaluation of test results showed that for a given w/c ratio, abrasion of concretes made of hard aggregates was almost identical to the abrasion of concretes made of soft aggregates, if shot blasting was used as a test method;
- Abrasion resistance of concretes increased markedly with the increasing abrasion resistance of aggregates;
- The effect of aggregates diminishes markedly with the increasing concrete strength.
- Air entrainment influences abrasion resistance only in so far as it affects the compressive strength of the concrete;

The Abrams' findings are simple and logical enough, but how does one select the test method for a meaningful result? It has been shown that close correlation between abrasion and compressive strength only exists for the tests with shot blasting. If the tests are carried out by the "steel balls in a drum" method or some "dressing wheel" method, eg Chaplin, then the abrasion resistance of the aggregates becomes more important than the compressive strength. Ref 11 also points out that the influence of aggregates becomes almost negligible when the concrete strength exceeds 55 MPa.

Comments:

1. *If there was any loss of abrasion resistance of the surface layer then it would be due to either the strength of the mortar paste or be aggregate related.*
2. *The aggregate properties would not change whether the curing temperature was below or above 5ºC. Hence this possibility can be eliminated.*
3. *Elsewhere in this Report it has been shown that there has been a constant and identical strength gain in the concrete strength, which is now well above the minimum requirement.*

4 *Even if there was some loss of strength in the surface layer of the mortar paste in the first 24 hours, it can be assumed that its rate of gain of strength would have been similar to that of the core strengths.*
5 *As the core strengths are well above the minimum requirements, it can be assumed that the mortar strengths are also above those of the 5 MPa concrete.*

9. Testing of Concrete for Resistance to Abrasion

Research to develop meaningful laboratory tests for concrete abrasion has been underway for more than a century, with no satisfactory test in sight. This is illustrated by the discussion in the previous section. As there are several different types of abrasion, no single test method has been found adequate for all conditions (Ref 1 p13), let alone for abrasion resistance. The accepted differing conditions are: high wear industrial floors, concrete road surfaces due to studded tires or chains, hydraulic structures and cavitation actions on concrete in dams, spillways, tunnels and other water carrying systems. The possible erosion between the subbase and base slab does not fall into any of these categories.

Accepting the RTA concern that the “poor durability” may only occur on the surface of the subbase, the following test methods have been assessed:

9.1 PAFV (as suggested by RTA)

Polished aggregate problems occur when the surface mortar and texturing wear away to expose the coarse aggregate. Because the cement paste does not have good wear resistance, the wear resistance of the concrete depends on the hardness of the aggregate used. (Ref 8 p54). Sometimes the Polished Aggregate Friction Value Number may be nominated for the coarse aggregate to be used. If that was the case, this would only apply to base concrete that is directly under traffic.

One would expect that this attribute of the aggregate does not change whether the concrete is cured at above or below 5ºC.

PAFV test is normally carried out on sealing aggregates, with the minimum PAFV Number also nominated. It does not lend itself to testing aggregate embedded in concrete.

9.2 Chaplin Test (also nominated by RTA)

This test is designed to test the wear resistance on industrial floors where 50-60 MPa concrete is used. The tester consists of three 75 mm dia by 20 mm wide hardened steel wheels mounted tangentially on a circular steel carrier plate. An electric motor rotates the plate at approximately 190 rpm. After a preset number of revolutions, the depth of wear is measured. On our 5 MPa concrete it is expected that it will “drill” into the concrete in no time and whatever the results, they will be meaningless for comparisons.

9.3 Schmidt Hammer

It is accepted that it has questionable correlation with strength of concrete, but it could give a comparative indication of the surface “strength” between different

Lots. This may be the simplest way of determining whether there is a thin layer of low temperature affected concrete mortar.

9.4 "Mahaffey Test"

In discussing the issue with David Mahaffey of Mahaffey Associates, he mentioned that he could perform a "plate pull off test" to gauge the mortar strength on the surface of the subbase concrete. For this test a small plate is glued to the surface of the concrete and after a predetermined time of curing, the force required to pull it off the surface is measured.

On reflection, as has already been mentioned, it is the quality of the aggregate that enhances the abrasion resistance and hence the comparison of mortar strengths would not give a true indication of abrasion resistance. That being the case, the comparison of core strengths would be more meaningful.

9.5 Comparison of Core Slices

The compressive strength of the top, say, 30 mm slice of a core and the next similar one could be checked. If there would be a significant difference in their compressive strengths, it could be argued that there is some cold weather effect on the surface of the concrete.

Comments:

1. There no way of determining what the effect of capping would be to these thin slices.
2. Parameters for meaningful results do not exist, eg if the top slice has a compressive strength of, say, 5 MPa and the middle one 7 MPa, neither would fail under the specification.

From the discussion in Section 8 above, it is obvious that none of these tests are appropriate.

9. Results of the Investigations

The foregoing sections have explained the general issues associated with durability of concrete.

There were five non-conforming Lots involved. In all cases automatic temperature monitoring of the ambient, concrete surface and internal temperatures were undertaken. Table 1 summarises these results from the graphical plots.

Table 1 Subbase temperatures and NCRs

Lot No	NCR No	Length (m)	Pour times		Ambient temp (ºC)				Surf temp (ºC)			Intl. temp(ºC)			Comments
			Start	Finish	Start	Min	Max	Range	Start	Min	Max	Start	Min	Max	
			750	1140	14	2	13	12	17	5.5	14	17	8	13	Conc conforms
			834	1305	9	-2	7	11	15	5.5	7	13	5	7	Conc conforms
24	141	445	1044	1515	8	-2	22	24	13	2	13	13	4	9	
25	141/1	341	1108	1645	8	-4	2	6	14	7	7	13	9	9	Tarp 20m
26	141/2	84	910	1310	9	-3	22	25	15	7	15	15	8	13	Tarp 20 m
27	141/3	151			Same paving as Lot 26										
28	144/1	303	1039	1648	8	-3	16	19	13	1	16	13	3	12	
29	144/2	106	920	1310	11	-2	?	13	11	2	?	13	3.5	?	Monitor malfunction
30	144/3	66	835	1140	11	-2	22	24	15	4	17	14	5	14	

Comments:

1 *On no occasion did the surface or internal temperatures drop below freezing point.*

2 *The minimum ambient temperature varied from -2ºC to -4ºC, with the corresponding minimum concrete surface temperatures from 1ºC to 7ºC. The internal temperatures of the Subbase were 9ºC to 14ºC.*

3 *On three occasions there occurred a temperature range in excess of 20 degrees.*

Conclusions:

1 *None of the lots actually froze.*

2 *With maximum day time temperatures of up to 22ºC, there is no realistic way of predicting if the overnight temperatures would fall below 5ºC. No Project Manager would call off the pour with this information.*

Details of the core strengths and strength gain are given in
Table 2 shows also the lowest air and surface temperatures that each of the Lots was exposed to. These results are represented by the graph in Figure 1.

Table 2 Subbase compressive strengths

Lot No	Minimum Temps		First cores		Second Cores		Third Cores	
	Air (ºC)	Surface (ºC)	Age (days)	Strength (MPa)	Age (days)	Strength (MPa)	Age (days)	Strength (MPa)
24	-2	2	9	5.5	21	8.5	35	11.1
25	-4	7	8	4.8	18	7.1	34	10.6
26	-3	7	7	4.2	17	6.7	33	10.6
27	?	?	7	5.2	17	6.7	33	8.6
28	-3	1	9	4.3	14	5.3	29	9.9
29	-2	2	8	4.9	16	6.7	28	9.7
30	-2	4	8	5.3	15	6.1	28	11.3
31			7	4.7	13	5.6		

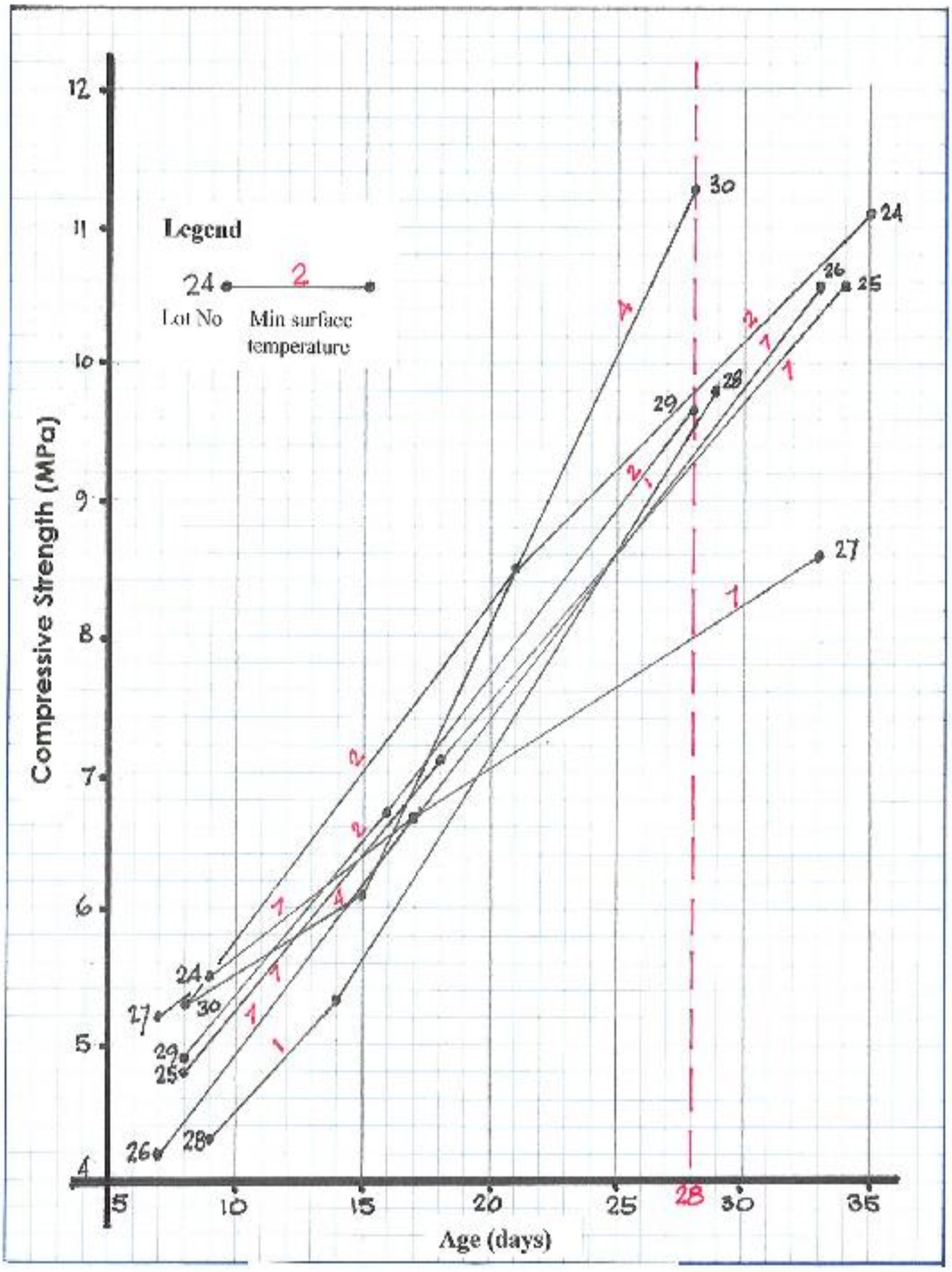

Figure 1 - Strength gain in individual lots

Observations:

1 *In all cases the specified strength requirements have been met or exceeded. (The table provides average strengths from a total of 103 cores).*
2 *Testing has been in accordance with RTA specifications.*
3 *In all recorded cases the surface temperature of the subbase never fell below freezing point.*
4 *The rate of strength gain in all the Lots is virtually identical.*
5 *The minimum surface temperature does not correlate with strength or the rate of strength gain – see Lots 26 and 29.*

Conclusions:

1 *The subbase and hence the free water did not actually freeze.*
2 *Because of the identical strength gains, it appears that the condition 7.6 from above, actually occurred, i.e. the concrete had acquired sufficient strength before the 5ºC threshold was reached and could withstand the internal pressures generated by the slight expansion of the remaining mixing water.*
3 *There was no observable detrimental effect to the surface layer of the subbase.*

Table 3 has been compiled to illustrate the availability of setting time and to substantiate the suggestion that in most cases the final set and definitely the initial set had occurred before the lower temperature threshold was reached.

Table 3 - Available setting time prior to temperature dropping below 5ºC

Lot No	Placement times		Time air	Setting time avalable		Comments	Core strength	
	Start	Finish	below 5ºC	From start	From finish		MPa	Age (d)
24	1045	1515	2100	10.45 h	5.45 h	Final set has taken place	5.5	9
25	1145	1645	1900	7.45 h	2.15 h	50% Final set	4.8	8
26& 27	915	1315	1800	8.45 h	4.45 h	90% Final set	av 4.7	7
28	1045	1645	1830	7.45 h	1.45 h	50% Final set	4.3	9
29	915	1315	1930	9.15 h	6.15 h	Final set	4.9	8
30	830	1145	2130	13 h	9.45 h	Final set	5.3	9

Observations:

1 *The virtually identical core strengths illustrate that there would have been sufficient time available for the internal strengths to be developed well in advance of the final set of the concrete.*
2 *All Lots behaved identically.*

10. Conclusions

1 Only some of the subbase concrete experienced temperatures outside those specified in the Contract. This occurred after the concrete had set.

2 No concrete was actually placed outside the specified ambient temperature limits.

3 None of the concrete actually froze.

4 Even with the below zero ambient night temperatures, the surface temperature of the subbase never fell below zero during the 24 hours after placement. (This is probably due to the heat of hydration).

5 The fact that the work did not satisfy one of the Specification requirements, regardless of how sound the concrete may be, would give the Client the right to require the Contractor to demonstrate that there are no detrimental effects in the surface layer of the subbase. In the absence of any mention of durability, abrasion resistance or erodability in the Specification, it is reasonable that the Client's concerns be evaluated in the light of overseas research and the actual conditions experienced.

6 It has been demonstrated that the time lapse between completion of placing of concrete and when the ambient temperature dropped below 5ºC was sufficient for the internal strength gain to occur and hence for the concrete to withstand any internal pressures that may have been generated by expansion of the free water.

7 It follows from point 6 above, that this would also apply to the surface of the concrete and thus there would be no detrimental effects to the durability of the surface layer.

8 As it has also been demonstrated that there is no suitable test method to verify the erosion resistance and that in this instance it is highly unlikely that the concrete suffered any detrimental effects, it can be assumed that the durability requirements were satisfied.

9 The Specification is silent on the disposition type of non-conformance. Hence, it may be assumed that Corrective Action is expected and required. This may take the form of curtailing the pours early enough to allow 6 hours for setting to take place before the cold night time temperatures or use suitable covers for the pavement to contain the heat of hydration. (The latter could make a difference of 5-7ºC.

10 Even though I believe that on the basis of overseas research, it can be assumed that the conditions experienced have not affected the durability issues of concern, Corrective Action in the Contractor's procedures is warranted.

11 My opinion is that the subbases as constructed are "fit for the purpose" and should be accepted "as is".

11. Postscript

1 Attention is also drawn to the occurrence of the actual freezing of a section of the subbase concrete during the construction of the Marulan By-pass (1984?). This occurred before the initial set of the concrete and was not apparent until it thawed out on the next day when the concrete was still plastic. It took 42 days for it to achieve the required minimum strength of 4 MPa. The work was then accepted by DMR

References

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9 Norbert Delatte: **Concrete Pavement Design, Construction and Performance** (2008)
10 QDMR: **Pavement Design Manual**
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14 RTA: Specification DCM R82 – **Lean-Mix Concrete Subbase**
15 US Army Corps of Engineers**: Extending the Season for Concrete Construction and Repair** (February 2004) [ERDC/CRREL TR-04-2]
16 UDoT: **Portland cement Concrete Pavement Specification** (January 2008)