FLY ASH UTILIZATION IN BRIDGE WORKS

Alberta Transportation and Utilities

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Abstract

The primary purpose of this project was to determine the extent to which two fly ashes readily available in Alberta affect the properties of concrete considered for use in bridge works, and accordingly to establish the conditions under which fly ash can safely be specified in such bridge works. The results confirm many potential advantages of using fly ash in air-entrained concrete, including reduced heat of hydration, the option to increase specified strength or reduce the unit volume cost, or some combination of both, particularly in massive bridge components, along with the prospect of satisfactory freeze-thaw durability under moist salt-free exposure conditions, increased resistance to chloride ion penetration, and reduced shrinkage potential. Most of these benefits are realized more fully using a superplasticizing admixture instead of a conventional water-reducing admixture. The main concern and limitation associated with fly ash utilization in bridge works is unsatisfactory scaling resistance under conditions of freezing and thawing with deicing salts. Criteria limiting such utilization have been established.

Key Words Concrete, bridge construction, fly ash, superplasticizing admixtures, air entrainment, heat of hydration, strength development, freeze-thaw durability, scaling resistance, chloride ion penetration, shrinkage potential.	**Distribution** Unlimited **Project Coordinator** Helen Tetteh-Wayoe, P.Eng.

ALBERTA TRANSPORTATION AND UTILITIES

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by

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INTRODUCTION TO FLY ASH UTILIZATION

The background against which this research program was undertaken is that the use of fly ash has to date been prohibited in Alberta Transportation & Utilities (AT&U) bridge specifications, despite the fact that large quantities of fly ash which constitute a waste disposal problem with environmental implications are produced by power plants in Alberta. Moreover, these fly ashes have many characteristics that rate them quite highly with respect to potential benefits in concrete compared with the broad range of ashes produced by power plants across N. America.

In particular, the unburned carbon contents of Alberta ashes determined by loss on ignition (LOI) values are extremely low, typically less than 0.5%, when compared with CAN3-A23.5 and ASTM C618 material specifications that permit use of fly ashes with up to 6% LOI. These low LOI values render the Alberta ashes much more amenable to the proper air-entrainment that is at least one of the prerequisites needed to ensure the durability of bridge concretes exposed to freezing and thawing. Nevertheless, previous work (ACI Concrete International, Vol. 16, No. 8, August, 1994, pp. 48-55) has clearly shown that for fly ash concretes air entrainment alone will not ensure adequate resistance to freezing and thawing cycles in the presence of a chloride-based deicing salt, so the purpose in this program is to better define the conditions under which fly ash can be used effectively and the equally important conditions under which use of fly ash should continue to be prohibited.

In view of the recent changes to current national codes like CAN3-A23.1 and ACI 318 which have replaced historically traditional water-cement ratio (w/c) requirements with often numerically identical requirements for water-cementing materials ratio (w/cm), it is important to realize that in reality a kilogram of fly ash is not equivalent to a kilogram of cement in terms of most performance criteria, despite precisely that implication in the current codes. In reality, fly ash may be better or worse than cement on an equal weight basis depending on which property or performance criterion is being assessed, and the effects may depend on the physical and chemical characteristics of the ash.

The following potential benefits and disadvantages associated with fly ash utilization in bridge works were identified in a preliminary background document forwarded to the Research & Development division of AT&U and the Bridge Engineering Branch on October 19/94 in an attempt to establish priorities for this project.

Potential Benefits

The issue of "when to use fly ash" depends on which of the following considerations apply and which are of highest priority for technical, economic and other reasons.

1. *Reduction in the unit volume cost of concrete* - Assuming the per tonne cost of fly ash as 20-40%* of the cost of normal Type 10 cement, there is the possibility of a materials cost saving in construction of large-volume bridge components. To achieve a worthwhile saving the amount of fly ash replacement of cement needs to exceed some critical minimum, likely of the order of 20% of total cementitious material.
   *Probably depends on haul distance from power plant to concrete plant, or to cement plant if blended cements eventually become available.
2. *Reduction in heat of hydration and consequent adverse affects in large pours* - To achieve a worthwhile reduction in heat of hydration the amount of fly ash replacement also needs to exceed some critical minimum, likely at least 20%. At this point is should be noted that Type 50 cement is also potentially useful in this regard. Compared with Type 10, Type 50 cements are reported to reduce heat of hydration by 25-40%. Obviously, combinations of Type 50 with fly ash could be even more effective, provided the cost premium (if any) for Type 50 is acceptable.
3. *Improvement in long-term strength (90 days onward)* - The present AT&U specification requirement for Class S is 20 MPa at 28 days with a w/c of 0.50 and no air void spacing factor limit. Our reference concrete with 340 kg/m^3 of cement and w/c of 0.50 (with conventional water-reducing admixture) reaches 30 MPa at 28 days with 7% air, good enough for a 25 MPa specification, but only reaches 33-35 MPa thereafter. Many fly ash concretes that we have tested would meet a 25 MPa 28-day specified strength criterion and the specified 0.22 mm maximum on spacing factor, and would qualify as AT&U Class B (possibly Class A also, but we have not used 40 mm aggregate in tests to date) except with respect to the specified w/c limit of 0.45. For example, 221 kg/m^3 of cement with 119 kg/m^3 of SU fly ash (35% of cementitious material) reached 38 MPa at 28 days and 47 MPa at 183 days in previous tests, but w/c is 0.71. Obviously, any increase in cement to decrease w/c impacts negatively on heat of hydration. Fly ash variability is also a concern in meeting strength requirements, to a greater degree than cement variability.
4. *Improvement in the long-term strength-cost ratio* - Some of the concretes evaluated with 35% or 50% fly ash reached strengths of 40-45 MPa between 90 and 183 days, compared to less than 35 MPa for equivalent concrete without fly ash. Perhaps there

are structural benefits from this higher long-term strength, for example reduced elastic deflection and creep. In any case the higher strength comes with a potentially reduced cost in terms of cementitious material.

5. *Possible benefits of superplasticizer use* - The previous points 1 to 4 have been discussed in the context of fly ash concrete with conventional water-reducing admixture only. Use of a superplasticizer permits lower w/c values and higher strength to be achieved without all of the increase in heat of hydration that comes with the only other alternative, that is increasing cement. Obviously, there is also a cost increase associated with its use that reduces the cost benefit gained from using fly ash. For example, a concrete with 287 kg/m^3 of cement and 155 kg/m^3 of fly ash (35% of cm) reached 59 MPa at 28 days and 68 MPa at 90 days with a w/c of 0.46. Cost in terms of cementitious material is estimated as equivalent to 349 kg/m^3 of cement compared with the 340 kg/m^3 of cement in the reference concrete (fly ash assumed at 40% the cost of cement).

6. *Reduction in chloride permeability and consequent build-up of chloride at the outer layer of reinforcement* - Most published data based on chloride diffusion tests at 20°C and 28 days show that chloride permeability reduces with increase in fly ash content. Recent results show that the reduction is temperature dependent, quite slight at 5°C with up to 50% fly ash, and very dramatic at 45°C. This suggests that when chloride supply by deicing is active in the winter months, diffusion could be more rapid than indicated by tests at 20°C. The source of this work has also tested precracked concrete and suggests that chloride penetration to steel is rapid when the cracks work continuously under load regardless of how impermeable the surrounding uncracked concrete might be. When cracks are left undisturbed healing can take place with a very favorable effect on chloride diffusion. Since cracks are often likely to develop in practice, the value of chloride diffusion tests at 20°C on uncracked concrete may be more limited than previously thought, especially in the context of cracks in bridge components subject to continuous working under traffic. The source also indicated greater reduction in chloride diffusion for fly ash concrete with silica fume compared to concrete with fly ash alone.

7. *Reduction in the potential for alkali-aggregate reaction (AAR)* - The consensus of published data is that fly ashes reduce the severity of the alkali-silica form of AAR, the form most likely in Alberta. Some ashes are more effective in this regard than others, but there is nothing to suggest that a fly ash could increase the severity of the alkali-

silica reaction. The alkali-carbonate reaction (not known in Alberta) is relatively unaffected by fly ash.

8. *Effect on sulphate resistance* - Low percentages of high-calcium-oxide fly ashes (CaO > 10%) may adversely affect sulphate resistance but higher percentages reverse this trend. Low-calcium-oxide ashes have a beneficial effect at all percentages. Alberta ashes with 7-9% CaO probably fall between these two extremes. Parts of Alberta have soils that are relatively high in sulphate, and the specified w/c of 0.45 is relevant in this regard. Any attempt to reduce it by increasing the amount of cementitious material is however in conflict with heat of hydration considerations.

The above points summarize my views on when and why Alberta Transportation might justify the use of fly ash for technical or economic reasons. The effect of fly ash source for the classified ash sources in Alberta has not been fully evaluated in previous work. Whether the use of unclassified (cheaper) ashes should be considered may also be relevant to the research program. The importance of source should be investigated in future work after all potential sources have been identified. A minimum material specification for fly ash is obviously CAN3-A23.5, but I believe that most classified Alberta ashes could meet a more rigorous and safer specification, notably with respect to LOI, SO_3, and possibly pozzolanic activity with cement. High LOI makes air entrainment more difficult. Wide variability in LOI makes air entrainment difficult to control.

Disadvantages and Limitations

The important issue of "when not to use fly ash" depends largely on freezing and thawing considerations. The consensus of published data indicates that properly air-entrained fly ash concretes pass ASTM C666 (rapid freezing and thawing in water to 300 cycles). However, there may be an upper limit on w/c, and an associated lower limit on cementitious material, beyond which some drop in durability factor occurs. Again the requirements for low heat of hydration and relatively low strength conflict with those needed for freeze-thaw durability, in this case an assessment of the concrete to internal disruption by freezing in a moist condition.

Of greatest concern in view of our recent project is the generally lower resistance to deicer salt scaling in 3% sodium chloride solution associated with all fly ashes. The worst-case performance is associated with top finished surfaces, so it is clear that fly ash use in decks and other highly salted finished surfaces is to be avoided. A mitigating factor is the somewhat better performance of bottom steel-formed surfaces. Type of formwork material could also be relevant. Presumably, the performance of vertically formed test surfaces falls somewhere between the top and bottom surfaces.

The limited results to date show that for bottom formed surfaces only a minority of the fly ash concretes tested achieve what the Swedish standard SS 13 72 44 rates as good resistance to scaling (< 0.5 kg/m^2) and not many are even acceptable according to this standard (< 1.0 kg/m^2) (Ontario criterion is < 0.8 kg/m^2). Those that come closest to meeting these criteria are relatively high in cementitious material (higher heat of hydration) and lower on w/c but not as low as 0.45. The best performances (0.2-0.5 kg/m^2 weight loss) have been achieved with a few superplasticized concretes with 35% fly ash, but even they do not quite meet the w/c limit of 0.45 with good scaling resistance according to our present test procedure. Whether it can justifiably be modified in some way is something to be considered. Modifications might include increasing the curing time before start of freezing beyond the standard curing regime of 14-days moist and 14 days at 50% RH. In this regard the deliberations of RILEM TC117-FDC, a task group formulating recommendations on this subject may be relevant. Among other things they recommend storage for 21 days at 65% RH followed by resaturation for 7 days before freezing starts. They support the use of 3% NaCl as the deicer under conditions which produce a uniaxial temperature gradient. The Swedish standard test is included as one of three recommended alternatives.

Another factor that recently was brought to my attention through contact with a Dutch source is the possible mitigating effect of curing compound. The source shows a substantial reduction in weight loss due to scaling when comparing specimens "wet-cured" with those treated with curing compound. This also raises the question of duration of the benefit, the merits of different curing compounds, and perhaps investigation of the benefits of the more expensive silane sealant currently applied to decks.

In summary, there are many good reasons that may justify the use of fly ash in bridge works, but the conditions under which it is likely to perform satisfactorily with respect to freezing and thawing with risk of deicer exposure need to be defined and the use restricted accordingly.

PROPOSED TESTING PROGRAM

At a meeting with AT&U personnel from Bridge Maintenance, Construction, and Research & Development on October 21/94 to obtain their feedback, the following points emerged as relevant to the testing program.

1. The applications envisaged for fly ash concrete are mainly pipe or drilled piles, pile caps, solid piers and spread footings where exposure to deicing salts is not intended and would likely be minimal due to unintended leakage or contact with spray or moist salty atmosphere. On the other hand, exposure to water or high humidity under freezing conditions is very probable.
2. The applications are often massive enough for minimizing internal stresses due to heat of hydration to be important.
3. The exposed surfaces are to a large extent vertically formed against plywood, steel or other special material to produce a "Rubbed Finish" or a "Bonded Concrete Surface Finish".
4. The current specification permits removal of formwork at times varying from 1 to 5 days after casting, and there is no requirement for application of curing compound thereafter.
5. The time between concrete placement and first exposure to freezing is expected to be a minimum of 1 month (fall construction), but could be several months (spring or summer construction).
6. The use of fly ash with or without superplasticizer should not substantially increase setting times or drying shrinkage potential.
7. The applications contain reinforcement, so resistance to penetration of water, oxygen and possibly unintended chloride deicer is important to minimize corrosion potential.
8. Durability under exposure conditions other than freeze-thaw is sometimes relevant, for example sulphate attack in high-sulphate waters or soils, or deterioration due to alkali-aggregate expansion with certain reactive aggregates.
9. There are two classified fly ashes available in Alberta from the Foresburg and Sundance plants. Other available ashes are not classified or refined to necessarily meet ASTM C618 or CAN 3-A23.5.
10. The fly ashes might be used in combination with Type 10, Type 30 or Type 50 cements as circumstances dictate, for example to avoid unduly slow strength development in cold weather, to minimize heat development even further in very massive pours, or to resist sulphate attack in high-sulphate waters or soils.
11. The effectiveness of air-entraining admixtures (AEA) and superplasticizing admixtures (SP) may be influenced by the presence of fly ash, specifically with regard to slump and air retention, setting times, strength development, and air void characteristics.

Subsequently, it was stated that spring, summer or fall construction could not necessarily be assumed, as indicated in 5 above, and that sulphate attack and deterioration due to alkali-aggregate reaction, as identified in 8 above were not a high priority. The basis for the schedule of tests initially proposed evolved from consideration of the above points.

Initial Basis for the Testing Schedule

The primary emphasis in the proposed 2-stage series of tests is on slump and air retention, heat of hydration, strength development, and scaling resistance for bottom and vertically formed surfaces using steel and plywood (or other materials deemed relevant by the client) to form the test surface that is ponded with either water or 3% sodium chloride during freezing. Special molds that will permit the attachment of any sheet material (plywood, steel etc.) to one vertical side to form the test surface will be built. Correlation of the scaling resistance of these surfaces with the resistance for standard bottom formed surfaces is desirable to link the results with earlier data for top and bottom surfaces. The correlation is examined only for mixtures likely to exhibit significant scaling. Curing regime with respect to duration of moist or in-formwork curing and subsequent drying, and with respect to the absence or presence of curing compound, is recognized as likely to influence both strength development and scaling resistance since scaling is a surface phenomenon and the surface is most severely affected by curing variables.

Each of the series of tests is planned for a maximum of 20 scaling specimens consistent with the capacity of the freezer. Since a scaling test to 50 cycles with one per working day takes about 10 weeks, there is the opportunity to appraise the performance of the mixtures under test for about 6 weeks before specimens for the next series are cast. Accordingly, the mixture proportions selected for the subsequent series of tests can be adjusted to reflect the trends in the results for the previous series. Likewise, the exposure condition most likely to give acceptable performance can be altered, as for salt versus water, on the assumption that acceptable scaling resistance with salt solution will correspond with at least comparable scaling resistance in water and unacceptable performance with salt may correspond to acceptable performance with water. Duration of moist curing can also be altered, or curing compound can be applied to determine any improvements for mixtures judged from earlier tests as likely to give unacceptable performance.

Secondary emphasis in terms of frequency of testing, but not necessarily importance, is on the resistance of the interior of the concrete, including the aggregate, to disruption by freezing and thawing in the water-saturated state, retardation of setting, shrinkage potential, chloride permeability and confirmation of the performance of the AEA in terms of the air content and air void spacing factor in the hardened concrete. The period of moist curing prior to the start of freezing in ASTM C666 has been increased from the standard 14 days to 28 days to allow the fly ash concretes to reach a maturity comparable to that reached before first freezing in practice.

The mixture proportions chosen reflect the experience of earlier preliminary tests with and without SP with regard to strength development and scaling resistance in 3% NaCl using up to 50% fly ash replacement. In view of the extensive work done by Malhotra and his co-workers at CANMET with high fly ash concretes (up to 67% replacement), and the exceptional strength development and satisfactory freeze-thaw resistance in ASTM C666 reported for these superplasticized high fly ash mixtures, the extent of fly ash replacement has been increased by a further 15% increment to 65% of total cementitious material. The first two digits of the mixture code reflect total cementitious material content (340, 380 and 420 kg/m^3 for mixtures without SP and 300, 340, and 380 kg/m^3 for those with SP). As the early results become available, adjustments to cementitious material and ash replacement levels may be indicated as appropriate for subsequently tested mixtures to meet strength and freeze-thaw performance criteria.

Final Testing Schedule

Following discussions with the sponsors after completion of Series I of the schedule of tests, the second portion of the schedule identified as Series II was modified to reflect the consensus of those discussions as summarized in my letter to Ms. H. Tetteh-Wayoe dated April 27/95. The final schedule of tests presented in Table 1 reflects these modifications.

MATERIALS

Coarse Aggregate - Blend of 600 kg/m^3 of 28 mm nominal maximum size gravel with 480 kg/m^3 of 14 mm gravel from a Calgary source (Table 2).

Fine Aggregate - Concrete sand from a Calgary source (Table 3).

Cement - Normal Type 10

Fly Ashes - Refined bagged ash from Sundance plant coded SU (Table 4). Refined bulk-delivered ash from Foresburg plant coded FG (Table 4).

Water-Reducing Admixture (WN) - Polyheed 997 supplied by Master Builders. Used at dosage of 300 ml/100 kg of cementitious material (cement & fly ash) where manufacturer indicates ASTM C494 Type A function i.e. water-reducing with normal setting tendency.

Superplasticizing Admixture (SP) - Product identified as SPN supplied by Master Builders. Used at various dosages dictated by water content and workability considerations, generally within the manufacturer's recommended maximum of 1000 ml/100 kg of cementitious material. Classed as ASTM C494 Type F i.e. high-range, water-reducing with normal setting tendency.

Air-Entraining Admixture (AEA) - Microair supplied by Master builders initially in a few control and low fly ash mixtures. Changed to MB AE 90 for most subsequent mixtures on advice of manufacturer. Used at dosages needed to achieve air contents in the range 5-8% identified for Category 1 exposure using 20 mm aggregate in CAN3-A23.1-M90.

MIXTURE PROPORTIONING

Concrete mixtures for bridge substructure components must on the one hand exhibit adequate strength development and durability with respect to freezing and thawing in a saturated condition in water, while on the other hand minimizing heat of hydration and cost in terms of total cementitious material. Accordingly, based on past experience showing that for the 28 mm gravel used the minimum cement content (without fly ash) capable of meeting the 0.50 limit for water-cement ratio, w/c, needed for freeze-thaw exposure when saturated with water, is 340 kg/m^3, the total cementitious material in the first series of mixtures was selected as 340 kg/m^3. Accordingly, the reference cement-only concrete against which the fly ash concretes are compared employs a conventional water-reducing admixture (WN) with 170 kg/m^3 of water to achieve the w/c durability limit of 0.50. The associated series of fly ash mixtures coded 34 maintains cementitious material constant at 340 kg/m^3 and incorporates fly ash percentages of 20, 35, 50 and 65% by weight of total cementitious material.

Fly ash mixtures with conventional water-reducing admixture (WN) are proportioned on the basis of estimating the water reduction achievable using the various percentages of fly ash and compensating for the resulting volume decrease due to water reduction and volume increase due to replacing cement with fly ash with an adjustment to the sand content while keeping the coarse aggregate blend constant throughout. Typical proportions for these 340 WN mixtures are shown in the following table.

Sample[a] Mixture Proportions for 34 and 34 SP Concretes

Mixture Code	Aggregate-kg/m³		Sand kg/m³	Cem. kg/m³	Ash kg/m³	Water kg/m³	Dosage-ml/100 kg		Slump mm(min.)	Init. Air % (min.)
	28 mm	14 mm					SPN	WN		
34/00	600	480	660	340	0	170		300	46(30)	5.5(22)
34 SU/20	600	480	630	272	68	166		300	54(28)	7.7(33)
34 SU/35	600	480	600	221	119	160		300	63(20)	7.7(25)
34 SU/50	600	480	580	170	170	154		300	58(29)	6.3(23)
34/00 SP	600	480	720	340	0	146	844		70(25)	6.9(18)
34 SU/20 SP	600	480	700	272	68	140	1211		57(31)	6.1(34)
34 SU/35 SP	600	480	685	221	119	135	1029		76(33)	6.3(25)
34 SU/50 SP	600	480	670	170	170	128	1221		69(35)	6.0(40)
34 SU/65 SP	600	480	655	119	221	122	1046		105(24)	6.7(29)

[a] - Corresponding FG mixtures may differ slightly in admixture dosages, slump and air content

A sequential series of mixtures with superplasticizing admixture coded 34 SP was developed on the same basis using water contents on average about 16% less than for the corresponding mixtures with WN admixture. The objective was to maximize the water reduction without substantially exceeding the manufacturer's recommended maximum dosage of 1000 ml/100 kg of total cementitious material. Dosages below or above this benchmark level reflect slight under-utilization or over-utilization respectively of the water-reducing capability of the superplasticizer. Typical proportions for these 340 SP mixtures are shown in the above table. The slump values obtained 20-35 minutes after mixing commenced confirm the placeability of the mixtures. The air contents obtained 18 to 40 minutes after mixing commenced reflect the time needed for adjustments to AEA dosage to achieve the intended 6-8% initial air content.

Mixture proportioning for 300 SP and 420 SP mixtures with 300 and 420 kg/m³ of cementitious material and superplasticizer was done on the same basis as described for 340 SP mixtures.

Mixing Regime

Mixtures without superplasticizer were batched in the normal way with water-reducing admixture (WN) at a fixed dosage of 300 ml/100 kg incorporated with air-entraining admixture (AEA) in the mixing water. When necessary, incremental additions of water or AEA were included to adjust slump and air content.

Mixtures with superplasticizer were sometimes batched initially with about half the coarse aggregate withheld so that workability was high enough, given the reduced water content, for the AEA to function effectively before addition of SP. The remainder of the coarse aggregate was then added giving a stiff mixture to which SP was then added to restore workability. In other cases the AEA was incorporated into the stiff mixture that exists when all aggregate is present before addition of SP. In both cases, following mixing with SP and preliminary estimation of slump and air content, incremental additions of AEA or SP were made to further adjust slump and air content.

FRESHLY MIXED CONCRETE PROPERTIES

The results for all mixtures are presented in numerical detail in Table 5.

Slump

Slump values for mixtures without superplasticizer are generally within the 50-70 mm range typically required in AT&U specifications (Table 5, 34 SU and 34 FG). The time of measurement that elapsed in minutes since mixing commenced is given in parenthesis after the slump value, recognizing that slump decreases with time particularly for superplasticized mixtures. For the superplasticized mixtures (all mixtures with code ending SP) slump is more variable because it depends quite strongly on the SP dosage level and on the time elapsed between the start of mixing and the slump measurement. Consequently, its measured value is relevant only to the extent that it confirms the placeability of the mixture, as it depends both on the SP dosage and the time of measurement. The issue of slump retention with time when using superplasticizers has been discussed in detail previously (ABTR/RD/RR-93/01) and reconfirming it was not a priority here.

Air Content

Air-meter air content measurements are also linked to time elapsed since mixing, recognizing that loss of air content with time may be attributable both to the presence of fly ash and the presence of a superplasticizer, as also discussed previously (ABTR/RD/RR-93/01). Air contents in Table 5 reflect the initial determination of air content after all incremental adjustments to SP and AEA doses and in some cases final values determined at or near the completion of casting, recognizing that these final values represent the worst-case air void system in the molded specimens used for freeze-thaw tests on hardened concrete.

Rate of Air Loss with Time - For mixtures with WN admixture and up to 50% fly ash, the cases where there were two measurements show that air loss over a 30-minute period is generally less than 0.5% (0.7% in one case). This is not really serious enough to require any special consideration in practice, given the precision of the test as noted in ASTM C231.

For superplasticized concretes with up to 65% fly ash, the rate of air loss with time is more noticeable, but does not appear to depend on the fly ash content, which is consistent with the minimal effect of fly ash on air loss noted above for concretes without superplasticizer. For these combinations of fly ash and superplasticizer, air loss as a percentage of the initial value correlates quite well with elapsed time between initial and final measurements (Fig. 1). This air loss which amounts to 1% of the initial value for each 2 minutes of elapsed time, or 30% loss after 60 minutes, appears to be primarily due the superplasticizer rather than the fly ash. On this basis, a concrete meeting the minimum air content of 5% sixty minutes after delivery should have an initial as-delivered air content of 7.1%.

Air content vs. AEA Dosage - Our experience in trying to estimate AEA dosage to produce initial air contents around 7% to ensure final air contents of at least 5% indicates that the fly ash absorbs AEA until its affinity for AEA is satisfied after which the AEA starts to entrain air. It does not seem to matter whether the AEA is activated in a relatively high workability mixture with about half the coarse aggregate held back prior to addition of SP, or is incorporated in a relatively stiff mixture with all aggregate present when it cannot be activated fully until workability is increased by adding the SP. In either case dosages increase significantly when SP is present and tend to increase only slightly with increase in fly ash percentage and increase in total cementitious material (Fig. 2). Dosages of AEA (Table 5) have reached as much as 2.0-2.5 times the manufacturer's recommended maximum (260 ml/100 kg of cementitious material for MB AE 90), but such high dosages do not seem to pose any special problems or have any obvious adverse effects in the hardened concrete.

SHORT-TERM HARDENED CONCRETE PROPERTIES

The results for all mixtures are presented in numerical detail in Tables 6 and 7.

Setting Times (ASTM C403)

Setting times determined on mortar sieved from the parent concretes and evaluated for penetration resistance in accordance with ASTM C403 are shown in Fig. 3. For superplasticized concretes with 50% fly ash there seems to be no significant difference in setting characteristics over the 300-420 kg/m^3 range of cementitious material contents. Initial set is 6.5-7.0 hour and final set 9.5-10.5 hour for all mixtures with or without superplasticizer and 50% fly ash, and there is no significant or consistent difference between the two ashes. The six superplasticized

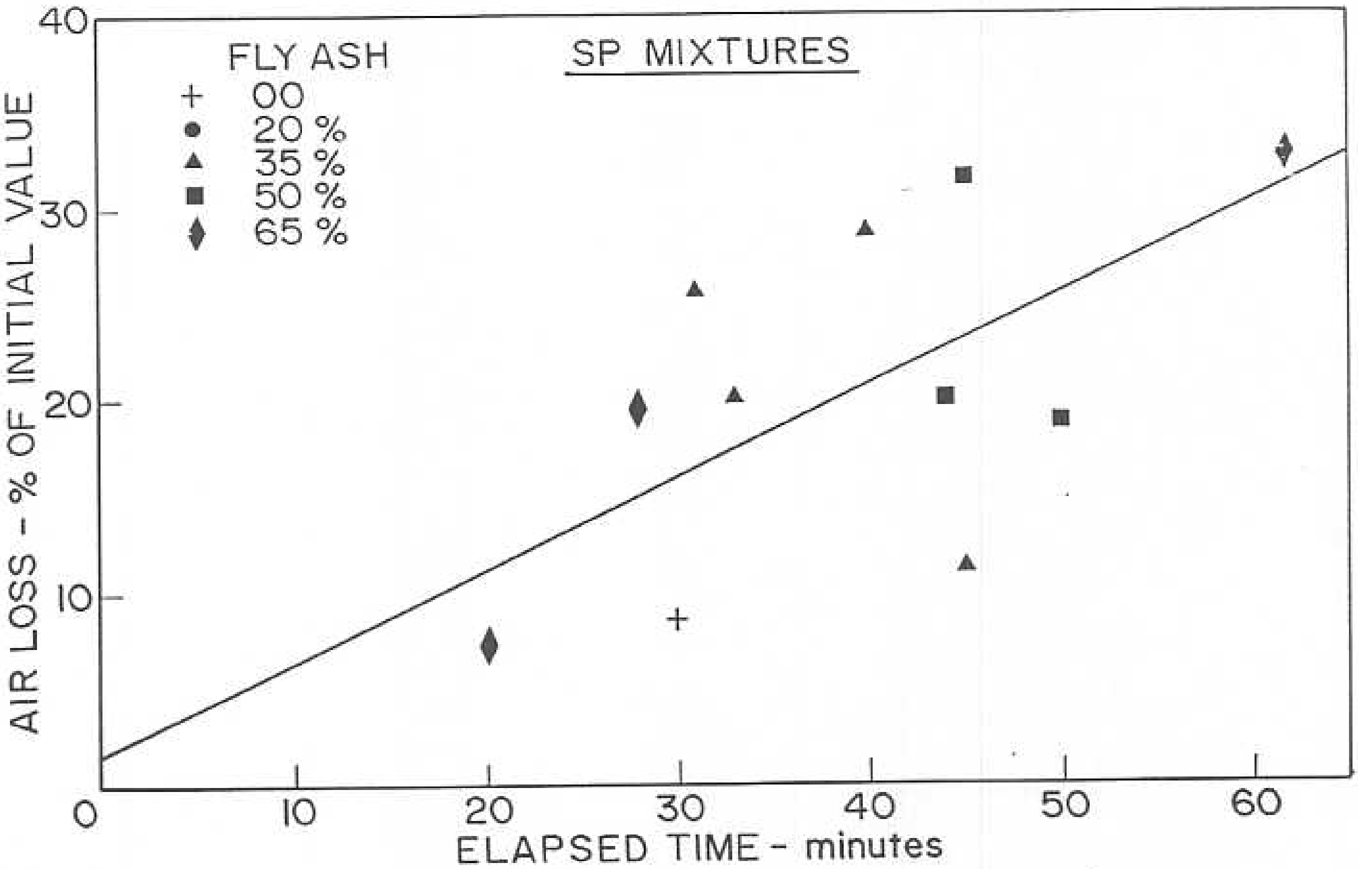

Fig. 1 Air Loss with Time for Superplasticized Fly Ash Concretes

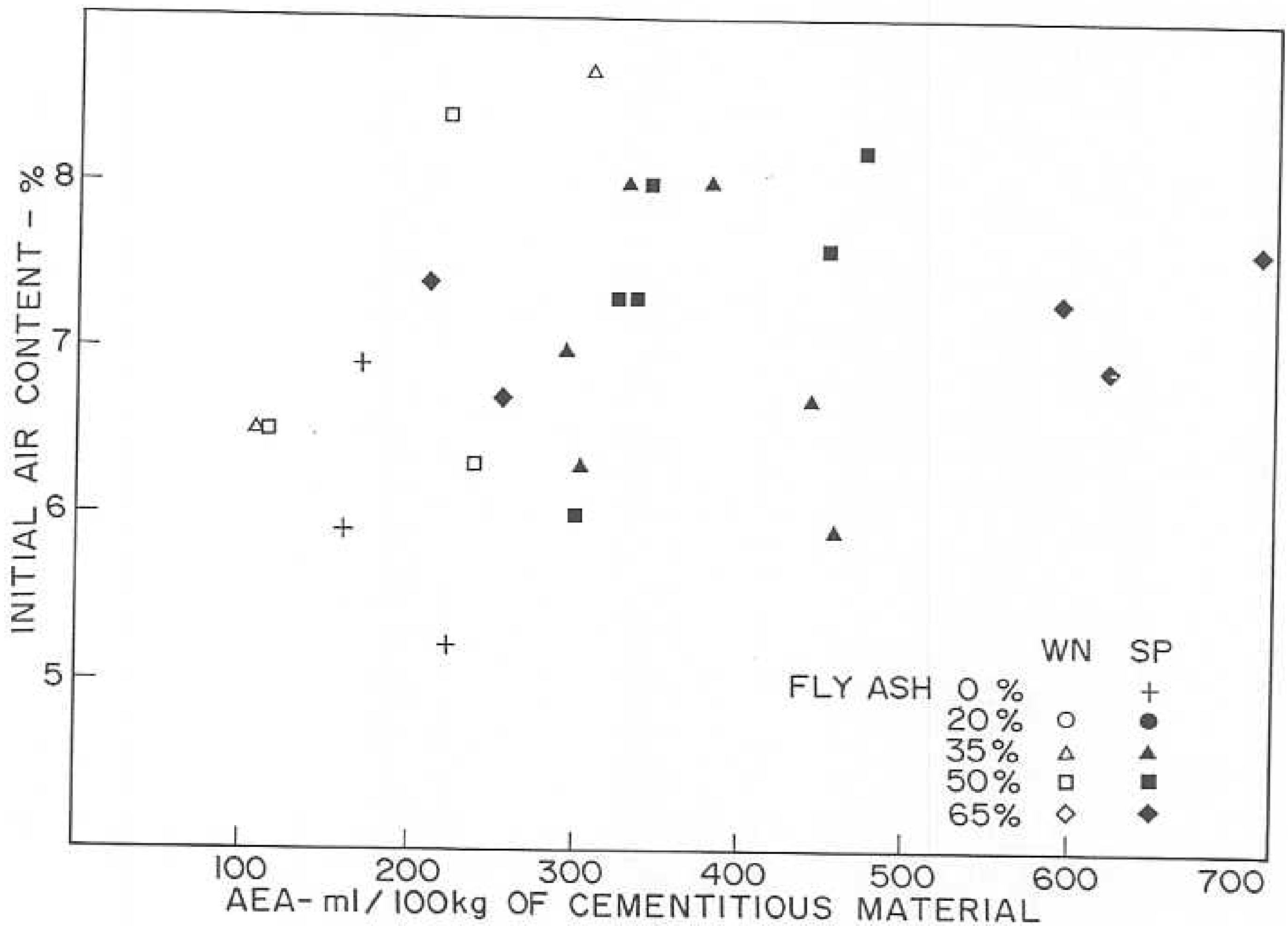

Fig. 2 Air-Entraining Admixture Dosage vs. Initial Air Content

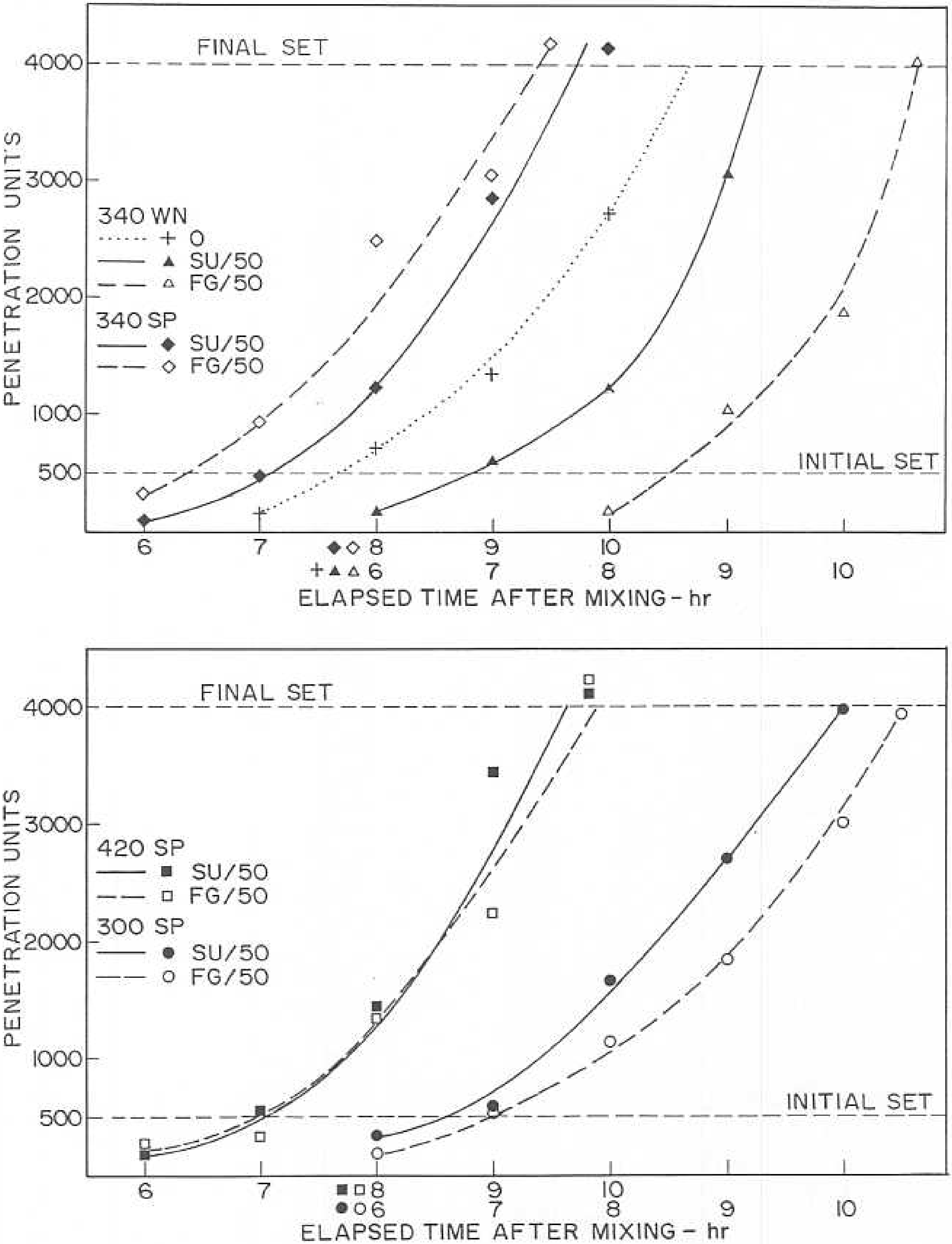

Fig. 3 Setting Characteristics of Concretes with 50% Fly Ash by Penetration Resistance (ASTM C403)

mixtures with 50% of either fly ash have slightly longer initial and final setting times than the control concrete without superplasticizer, but the difference is no more than 1-2 hours at the 23°C test temperature. Such a difference is unlikely to create difficulties in practice, and may even be advantageous in hot weather, but it may be greater and its consequences more important for cold-weather placement.

Heat of Hydration

All mixtures were evaluated for heat of hydration using a specially made styrofoam-lined insulated container with the styrofoam shaped to accommodate a 150 mm diameter cylinder vertically. The specimen was molded using a standard 300x150 mm mold, but filled only to a height of about 275 mm to allow for a styrofoam plug attached to the styrofoam lid of the container to fit above it. A thermocouple was molded into the specimen close to its vertical axis approximately at the mid-height. It was connected by wires run through the styrofoam plug to a paper tape data acquisition system on which temperature was recorded every half hour. The maximum temperature reached and the time after mixing to reach it are given in Table 6.

Maximum temperatures reached are as expected strongly affected by the presence of fly ash (Fig. 4). However, for the main series with 340 kg/m^3 of cementitious material, variables such as the presence of superplasticizer or type of ash have little effect. Raising the total cementitious material by 24% to 420 kg/m^3 increases the maximum temperature reached by about 5°C. While reducing total cementitious material from 340 to 300 kg/m^3 might be expected to have the reverse effect there is insufficient data to be conclusive, and for the 35 and 50% fly ash contents evaluated the temperature drop is less than expected.

The time to reach the maximum temperature is least for control mixtures with an average of about 22 hours, increases only slightly to 24-25 hours for fly ash contents of 20, 35 and 50%, and increases to 29 hours on average for mixtures with 65% fly ash.

No container is completely able to prevent heat loss, and specimens that are massive are less affected by surfacial heat loss. The numbers for maximum temperature with insulated standard 150x300 mm diameter cylinders differentiate the mixtures at least in a relative sense, clearly demonstrating the benefit of fly ash in reducing heat of hydration in large structural elements.

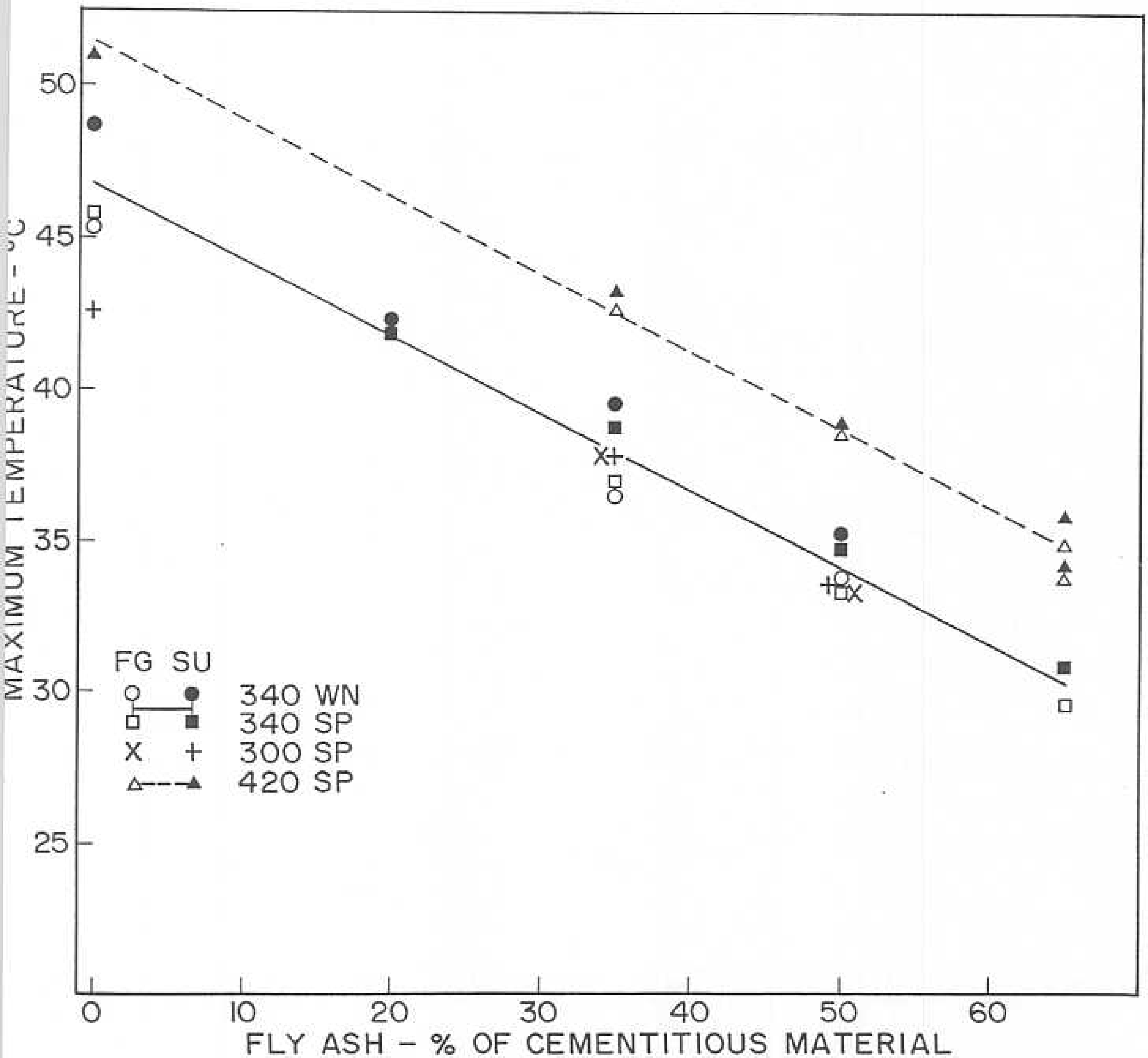

Fig. 4 Heat of Hydration Characterized by Maximum Temperatures Reached in Insulated 150 mm Diameter Cylinders

Strength Development

The results of the average of strengths determined on pairs of 150x300 mm cylinders are reported in terms of fly ash content and age at test in Fig. 5, 6 and 7 for 7, 28 and 90 day ages respectively.

Comparing the data sets for 340 kg/m^3 of cementitious material with superplasticizer, 340 SP data, and with water-reducer, 340 WN data, shows that the SP mixtures with water content, w/c and w/cm ratios 16% lower on average are significantly stronger at all test ages. The influence of the superplasticizer is slightly greater at higher fly ash contents and later ages (Fig. 6 and 7) where it accounts for an increase in strength of the order of 10 MPa.

Comparing the data sets for 300 kg/m^3 and 420 kg/m^3 of cementitious material it can be seen that the 40% increase in cementitious material raises strength by about 10 MPa at the 50% fly ash content and rather less at lower fly ash contents. Naturally, this causes substantially increased heat of hydration, so it is clear that maximizing strength without affecting heat of hydration is best achieved with superplasticizer. The same conclusion is reached when it is observed that strengths for 300 SP mixtures are at least equal to those for 340 WN mixtures despite having 12% less cementitious material.

The trend lines shown in Fig. 5, 6 and 7 are judgemental rather than statistical and attempt to establish whether there are consistent differences between the FG and SU fly ashes in terms of strength development. For the 340 WN data set there is no clear difference between the two ashes. For the three data sets with superplasticizer, 300 SP, 340 SP and 420 SP, there is a fairly consistent pattern showing strengths higher for the SU ash than the FG ash, particularly at age 28 days with the difference lessening slightly at age 90 days. This is consistent with the greater fineness (less retained on 45 μm sieve) and higher pozzolanic activity values given in Table 4.

To examine the extent to which the apparently random ups and downs in strength data are indeed random, two other factors were examined.

Effect of Air Content Differences - The first and most obvious factor for consideration is air content, since it is generally recognized that strength changes about 5% for every 1% change in air content. However, when this is considered in the context of the air content spreads within each data set (Fig. 8) and in the context of the precision associated with air content measurements (ASTM C231 states that the difference between two tests by different operators on the same mixture should not exceed 0.8%) the influence of air content is quite minor. For example, in the 340 SP data set the strength difference between the SU and FG ashes at 50% fly ash content attributable to the 1.3% difference in air content amounts to 6.5% (5x1.3), about 2.6 MPa at 28 days and 3.1 MPa at 90 days, while the actual difference is 10 MPa at 28 days

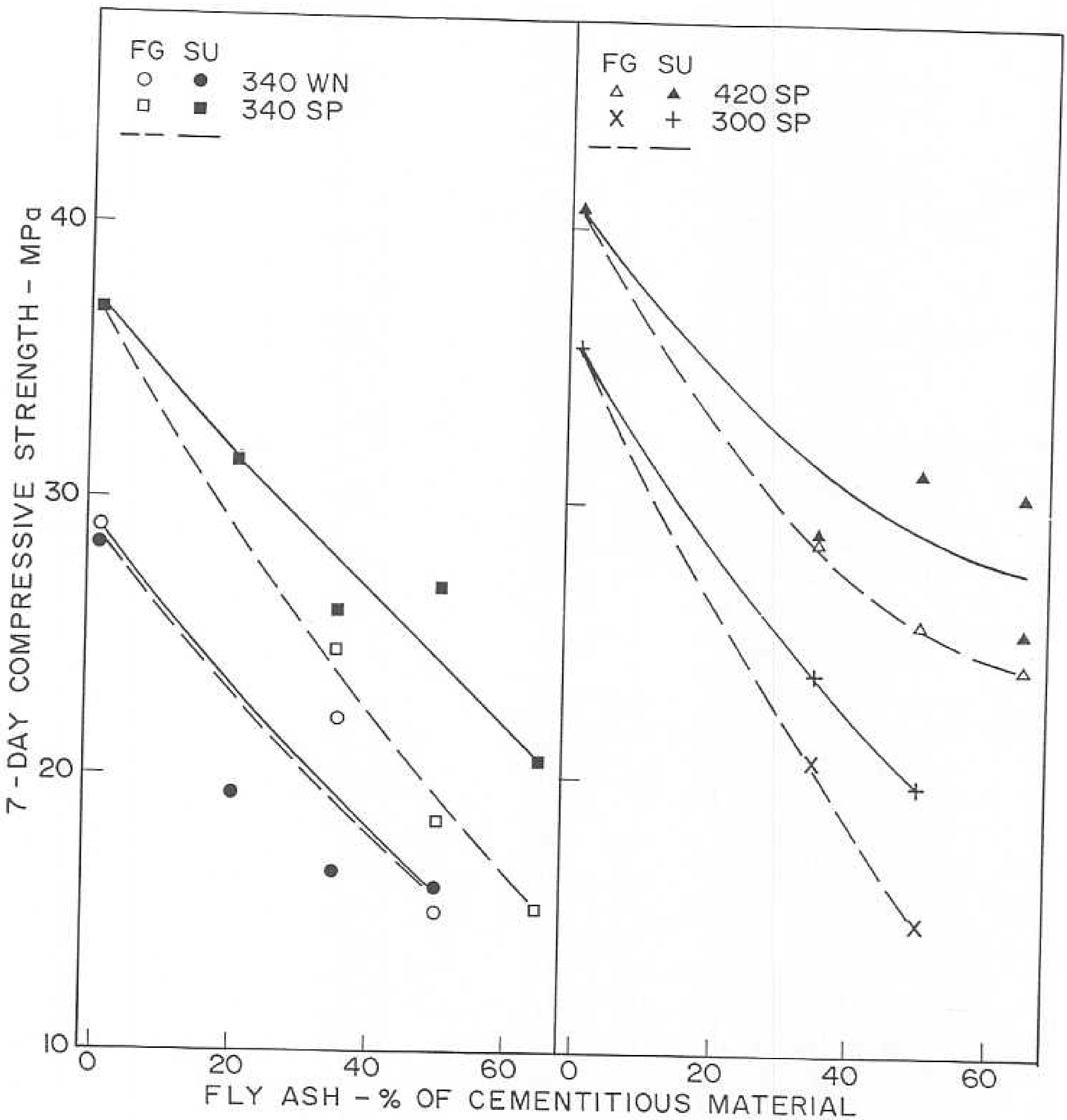

Fig. 5 7-Day Compressive Strengths

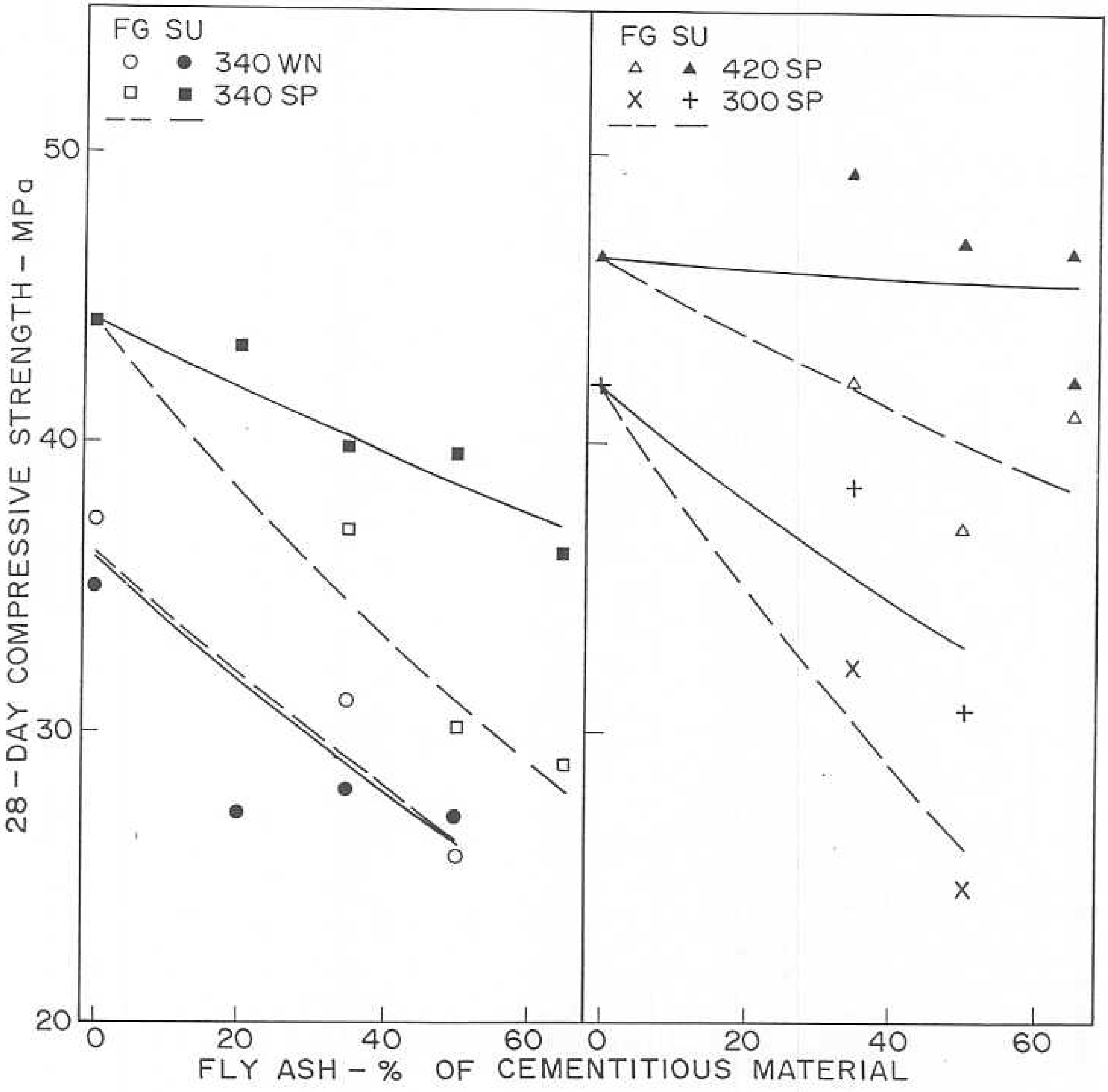

Fig. 6 28-Day Compressive Strengths

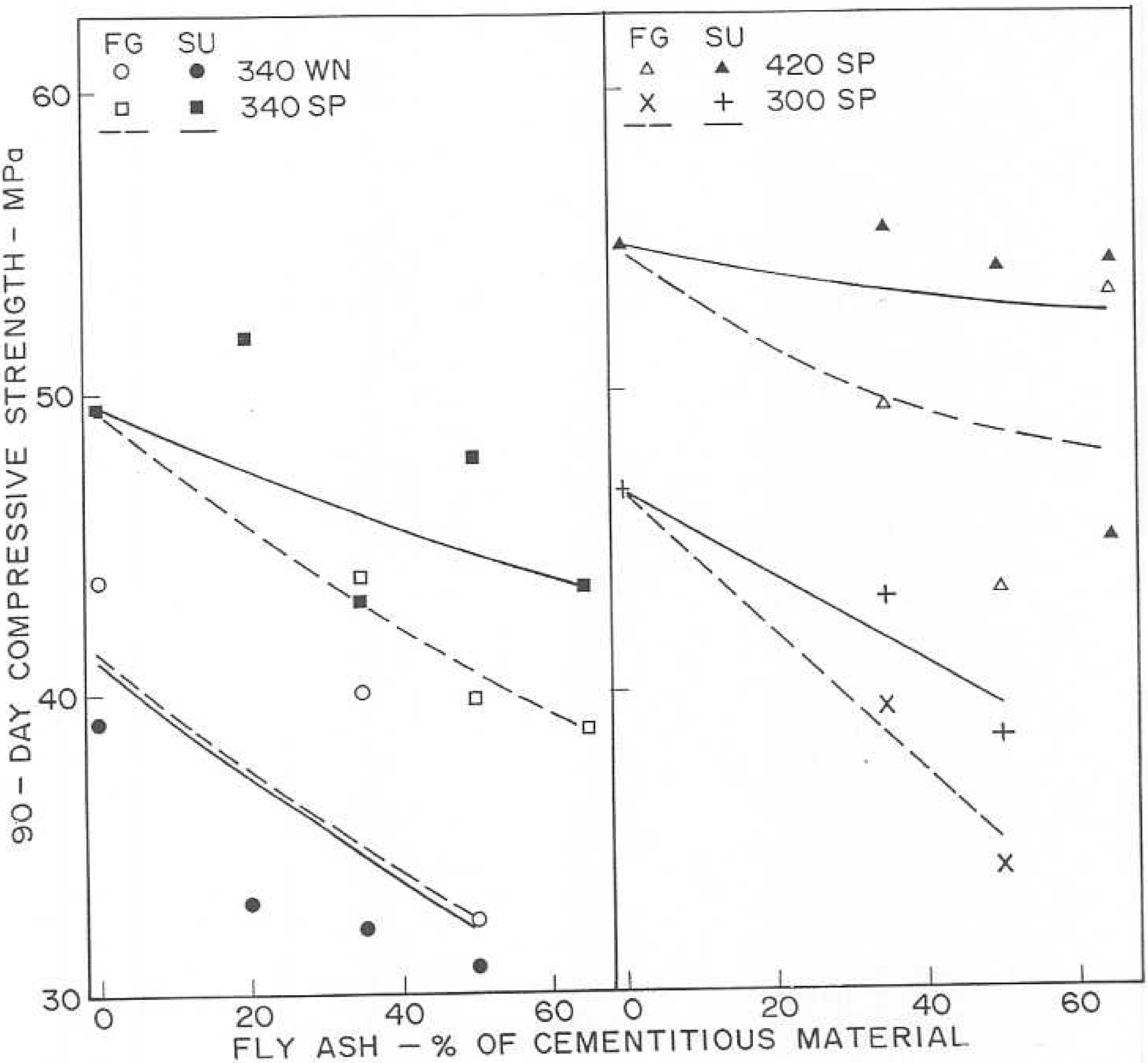

Fig. 7 90-Day Compressive Strengths

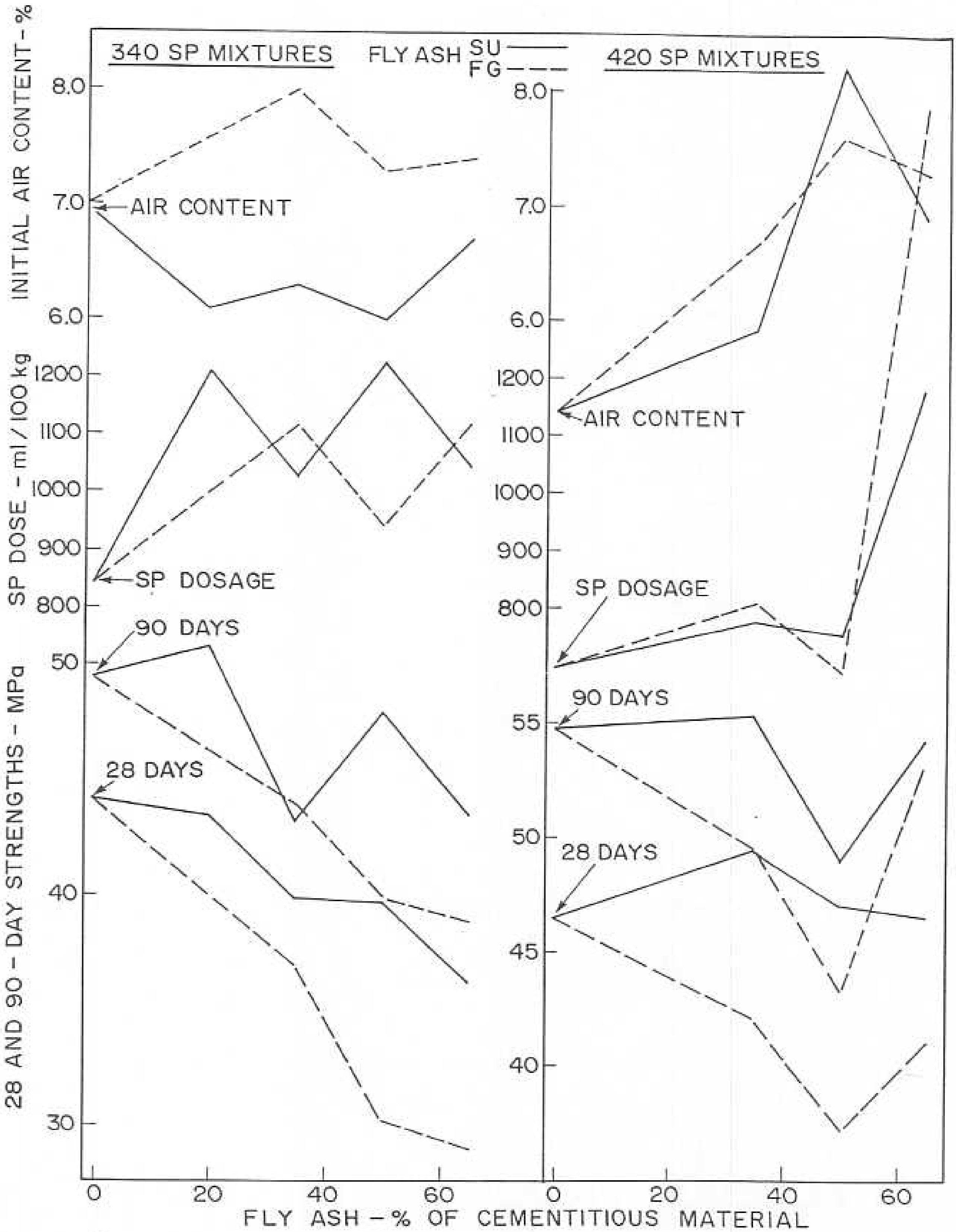

Fig. 8 Comparative Trends for Air Content, Superplasticizer Dosage, and Compressive Strength

and 8 MPa at 90 days. At the 65% fly ash content the air content difference is only 0.7%, equivalent to 1.3 MPa at 28 days and 1.5 MPa at 90 days, but the actual strengths differ by 7 MPa at 28 days and 5 MPa at 90 days. In the 420 SP data set the air contents happen to coincide quite closely for the SU and FG mixtures, but the trend of lower strength for the FG ash is consistent except at the 65% ash content. This exception is discussed in the next section.

Effect of SP Dosage Differences - The second factor examined is SP dosage (Fig. 8). This reveals that the exceptionally high strength for the FG ash at the 65% level in the 420 SP data set is apparently associated with an abnormally high dosage of SP. This is consistent with a trend visible in much of the data, for example most obviously in the 90-day strengths for the 340 SP data set, and still noticeably in the 28-day strengths for this data. Apparently, higher strengths are associated with higher SP dosages regardless of any secondary influence of differences in air content.

Clearly, the SP has a major effect on strength development that increases with increased dosage particularly at the higher fly ash contents. Presumably, greater dosages promote better dispersion of the cement and fly ash particles to improve both the rate of hydration and the total degree of hydration achieved at later ages, in this case up to 90 days. The pattern of only slight decrease in 90-day strength as fly ash content changes from 0 to 65% is inconsistent both with the corresponding dramatic increase in w/c or the slight decrease in w/cm (Table 6), confirming that fly ash is not equivalent to cement on a 1:1 basis. This is contrary to what is implied in the current CAN3-A23.1 which uses w/cm requirements for various exposure conditions equal to the corresponding w/c requirements specified in the 1977 edition.

Strength v. Cost of Cementitious Material

In this comparison fly ash is considered as costing 40% of cement and cost is expressed as equivalent kg/m^3 of cement (Fig. 9).

SU Ash - Much higher strengths are possible for superplasticized mixtures than for mixtures with conventional water-reducer, or alternatively the SP mixtures can achieve the specified strength at considerably less cost in terms of cementitious material. For example, a 35 MPa average strength (suitable for 30 MPa specified strength) is achievable at a cost saving equivalent to about 143 kg/m^3 of cement when comparing 340 SP data slightly extrapolated with 340 WN data (Fig. 9, left), that is a mixture with 70% ash in 340 kg/m^3 of cementitious material versus a mixture with 340 kg/m^3 of cement alone. Offsetting the reduced cost of cementitious material is the cost of the required SP dosage, approximately 1000 ml/100 kg of cementitious material or 3.4 litres per cubic metre, less the cost of the WN dosage of 300 ml/100 kg of cementitious material which is about 1 litre per cubic metre.

Assigning dollar values to these costs is always difficult because of commercial factors. My inquiries suggest using cement at \$145 per tonne, fly ash at \$58 (40% of cement), SP at \$3 per litre and WN at \$3 per litre. On this basis a 143 kg/m^3 decrease in equivalent cement cost plus the cost of 1.0 litre of WN admixture amounts to \$21 + 3 = \$24, and is offset by the \$10 cost of 3.4 litres of SP admixture, leaving a net cost reduction of \$14/m^3.

Alternatively, the user/specifier might wish to decrease the 70% replacement level to about 40% to realize an 82 kg/m^3 decrease in equivalent cement cost with an increase in strength to 40 MPa along with improvement in some other properties such as reduced heat of hydration. In this case the net cost reduction is only \$2/m^3. If the cost reduction in equivalent cement plus WN admixture were to just offset the cost of SP in the 340 SP data, this would correspond to about 25% fly ash replacement and an average strength of 42 MPa, still with considerably reduced heat of hydration (Fig. 4).

Considering the 420 SP data set compared with the 340 WN data, even greater strength is possible combined with cost savings. For example the superplasticized mixture with 420 kg/m^3 of cementitious material and 65% fly ash achieves a strength of about 45 MPa compared with the 35 MPa for 340 kg/m^3 of cement with water-reducer. The cost reduction for 83 kg/m^3 less in equivalent cement is \$12/m^3 plus \$4/m^3 for WN admixture. It is offset by the \$13/m^3 cost of SP admixture, so the greatly improved strength with reduced heat of hydration (Fig. 4) is achieved with a small decrease of about \$3/m^3 in cost.

<u>FG Ash</u> - The corresponding data for this ash (Fig. 9, right) show that improvements in strength, or cost reduction, or a combination of both are possible, but to a lesser degree. For example, the 340 SP mixture with about 30% fly ash achieves the 35 MPa strength of the 340 WN mixture without fly ash at a cost saving in equivalent cement of about \$9/m^3 plus \$3/m^3 for WN admixture. This is offset by the \$10/m^3 cost of SP admixture, giving a net saving of \$2/m^3 along with reduced heat of hydration (Fig. 4).

Again, higher strength is possible when the 420 SP data is compared with the 340 WN data. For example, 38-40 MPa is achievable at the 65% fly ash level where the cost reduction for 83 kg/m^3 less in equivalent cement is \$12/m^3 plus \$4/m^3 for WN admixture. It is offset by the \$13/m^3 cost of the SP admixture, so slightly improved strength with considerably reduced heat of hydration (Fig. 4) is achieved with a small decrease in cost.

<u>Summary</u> - The foregoing examples reflect dollar costs available at the time of writing and are intended primarily to show what range of technical and economic benefits may be possible using

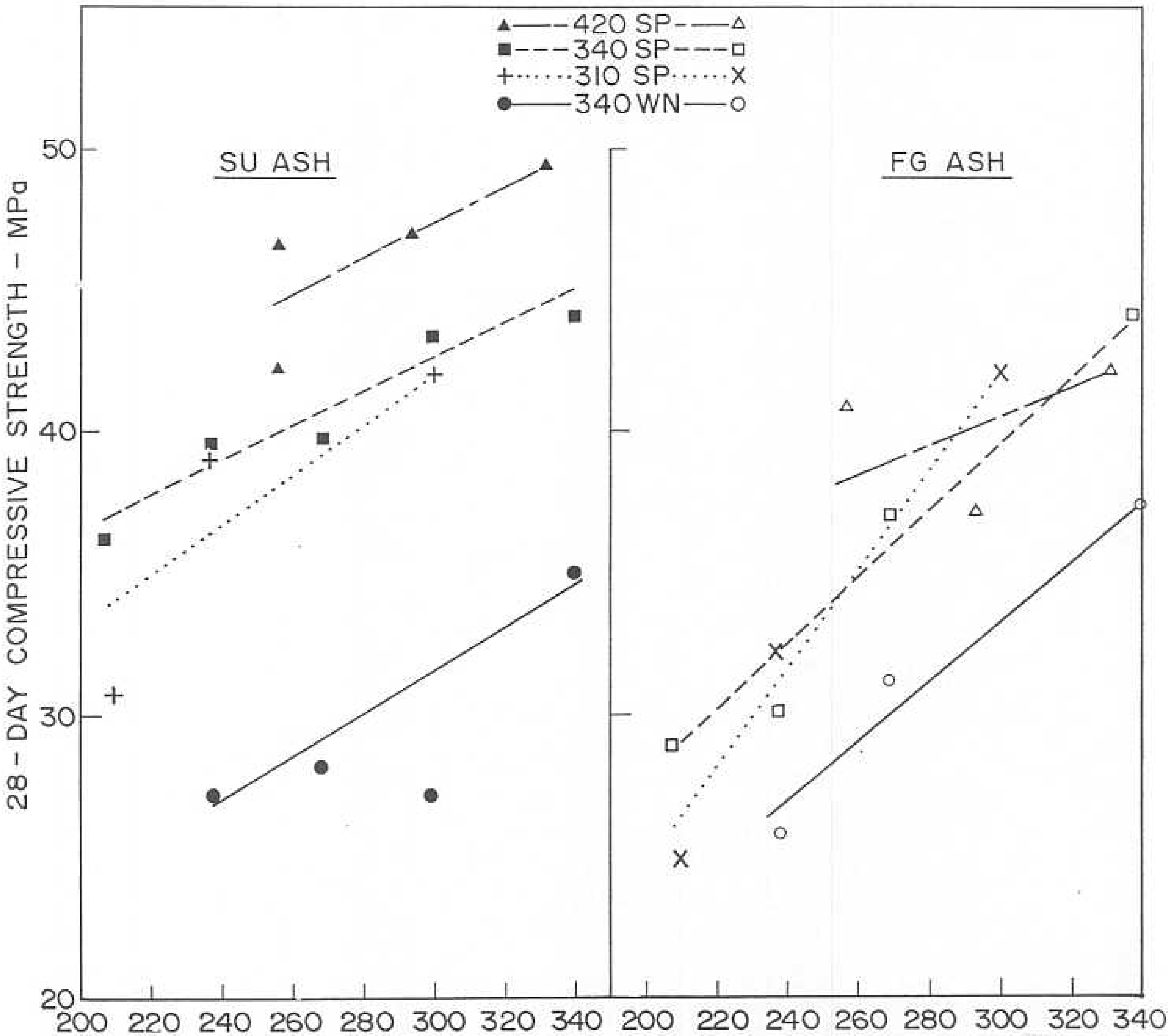

Fig. 9 28-Day Compressive Strength vs. Cost of Cementitious Material superplasticized fly ash concretes. Obviously, the benefits will change with change in the performance and cost of the cement, fly ash, superplasticizing and water-reducing admixtures, and other combinations of cost and materials should be evaluated as appropriate to the application considered. Nevertheless, some fly ash-superplasticizer combinations, such as those evaluated herein, seem to offer good potential for improving strength and reducing both heat of hydration and cost. Furthermore, where construction conditions involve pumping, fly ash tends to improve mixture pumpability.

Effect of Curing Conditions on Strength Development

In addition to cylinders tested for strength after standard curing (1 day in molds followed by moist curing in fog room for 27 days at 23°C) pairs of companion cylinders were subjected to restricted moist curing followed by air curing at 50% relative humidity, or an extended period in the molds followed by application of curing compound and storage at 50% relative humidity. Table 7 gives percentage reductions in strength relative to a reference 28-day strength for standard moist curing (negative values are increases).

The conditions of mold-curing for first 24 hours followed by 2, 4 or 6 days moist curing and then air curing at 50% R.H. to age 28 days, identified respectively as 3M/25D, 5M/23D, and 7M/21 D, affect strength in different ways (Fig. 10, left). Strength losses tend to increase from insignificant, less than 5% at low fly ash contents, to as much as 20% at higher fly ash contents for the 340 WN and 340 SP mixtures cured moist to age 3 days. When this initial period of moist curing was increased to 5 days, as for the 420 SP mixtures, and to 7 days for the 300 SP mixtures, strength losses are only more than 5% in one case (420 SP mixture with 65% FG ash).

The conditions of mold-curing for 1, 3, 5 and 7 days followed by application of curing compound and storage to age 28 days, identified respectively as 1M/27 CC, 3 M/25 CC, 5 M/23 CC and 7 M/21 CC, also affect strength in different ways (Fig. 10, right). Strength losses are quite severe when curing compound is applied after 1 day, and increase with increasing fly ash content to as much as 35-40% for the 340 WN and 340 SP mixtures. The losses become less severe, but still significant, up to 20%, when curing compound is applied after 3 days, and only cease to be significant when application of curing compound is delayed to 5 or 7 days.

Accordingly, it appears that when moist curing is practical it should be maintained for at least 5 days, and when moist curing is not practical forms should be kept in place for at least 5 days before curing compound is applied. Otherwise, significant strength losses may occur particularly at higher fly ash contents.

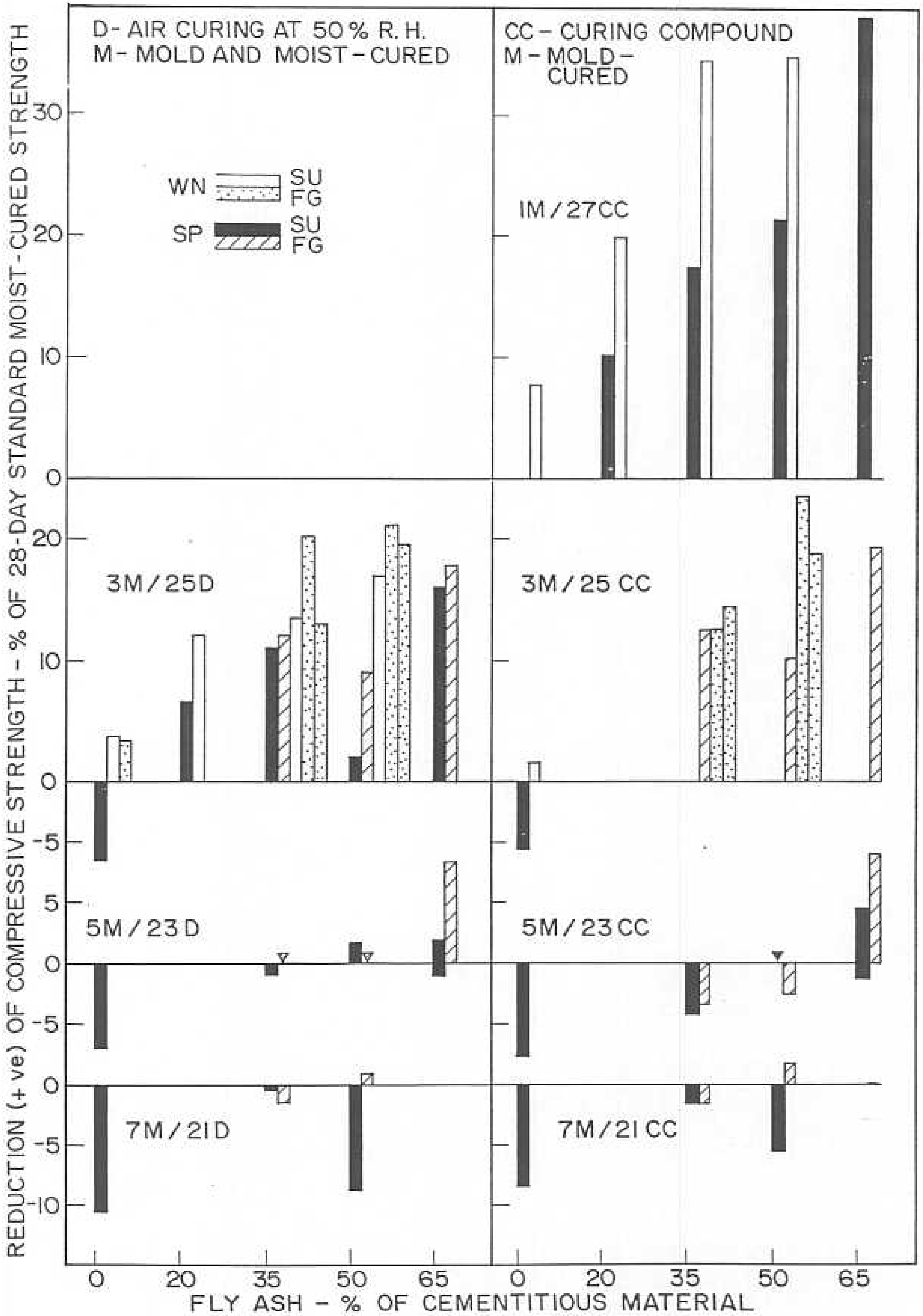

Fig. 10 Effects of Air-Curing at 50% Relative Humidity or Coating with Curing Compound on Compressive Strength Development to Age 28 Days

LONG-TERM HARDENED CONCRETE PROPERTIES

Certain mixtures were selected for evaluation of freeze-thaw performance in fresh water, scaling resistance in presence of 3% sodium chloride solution, length change on drying, and electrical conductivity with respect to chloride ion penetration. The selections were made on the basis of trying to define the limits separating satisfactory versus unsatisfactory performance, particularly with regard to freeze-thaw testing, or on the basis of confirming with minimal testing that high fly ash concretes do not have any special problems where none are anticipated, as, for example, with respect to shrinkage potential.

Rapid Freezing and Thawing in Water (ASTM C666 Proc. A)

The 14-day moist curing period specified in ASTM C666 was extended to 28 days in this testing program. The results shown in Fig. 11 are the averages for pairs of 380x75x75 mm prisms tested to 300 cycles at a rate equivalent to 6-8 cycles every 24 hours. The durability factor calculated from fundamental transverse resonant frequency measurements typically remains at 100 $\pm$ 10 for concretes unaffected by the freeze-thaw regime. Any internal cracking caused by the volume increase due to freezing is detected by a decrease in durability factor which is considered a failure (ASTM C494) when its value drops below 80.

The supplementary criteria introduced in recent years in C666 are length change and weight loss. Specimens exhibiting abnormal increase in length are considered to have suffered internal damage due to the expansive forces exerted by freezing. However, there are no interpretation guidelines as to what constitutes excessive expansion, although the literature suggests that concrete cured in water expands by 50-60 μm (0.005-0.006%) over 90 days and by ultimately as much as 150 μm (0.015%). If this applies to the concretes tested here, the total expansion is greater than the 90 day expansion due simply to curing in water during the thaw cycle, but the stress-relieving effect of creep makes it impossible to know whether this means internal damage or not. The resonant frequency measurements, that in most cases indicate satisfactory durability factors (> 80), suggest that the expansive length changes are not excessive.

No guidelines are given in ASTM C666 as to what constitutes excessive weight loss. This weight loss takes place as a result of surface scaling. Since the scaling tests on slabs described in the next section are based on weight loss in kg/m^2 of tested area, the weight losses recorded in C666 are expressed in the same units using the total surface area calculated for the test prisms. These weight losses represent scaling in water after 300 relatively rapid cycles starting at age 28 days, and may be compared with the slow cycle (1 every 24 hours) scaling tests on slabs reported in the next section that also started at age 28 days.

On the basis of durability factor, nearly all the mixtures comfortably exceed the generally accepted pass criterion of 80 minimum. Most have durability factors over 90. The remaining three are between 75 and 85 and apply to the FG ash used in the 340 WN mixtures with 35 and 50% fly ash and to the 340 SP mixture with 65% fly ash. These three mixtures also exhibit high weight losses due to scaling, generally in the 0.5-1.0 kg/m^3 range. All mixtures evaluated with the SU ash exhibit satisfactory performance in terms of both durability factor and scaling resistance in water. Thus, the threshold associated with satisfactory performance with respect to freezing and thawing in water may be fly ash source-dependent, as well as possibly dependent on w/c, w/cm and air contents. However, the three borderline mixtures with FG ash, 340 WN with 35% and 50% ash and 340 SP with 65% ash, do not differ significantly in w/c or w/cm, nor unfavourably in terms of air content, from the corresponding mixtures with SU ash, again suggesting that performance is ash source dependent.

All mixtures including these three borderline cases meet the current CAN3-A23.1-M90 maximum for w/cm of 0.50 for Class F exposure (freezing and thawing in saturated conditions without deicers). Furthermore, many of the 300 SP, 340 WN and 340 SP mixtures evaluated do not have 28-day average strength high enough (35 MPa in Fig. 6) to meet the A23.1 specified strength requirement of 30 MPa, although they exhibit satisfactory performance in the freeze-thaw test. The combined limits of 0.50 for w/cm and 30 MPa for specified strength exclude a number of 300 SP, 340 WN and 340 SP fly ash mixtures which demonstrate satisfactory freeze-thaw performance, but on the other hand all fly ash mixtures meeting both of these requirements exhibit satisfactory freeze-thaw performance, notably the 340 SP mixtures with 50 and 65% SU ash and the 300 SP mixture with 35% SU ash, which of those that meet both code requirements are the lowest in cost (Fig. 9) and heat of hydration (Fig. 4).

<u>Freeze-Thaw Scaling in 3% Sodium Chloride or Water (Modified ASTM C672)</u>

The adopted testing procedure evalutes specimens according to the size and freezing regime requirements of C672 but uses weight loss in kg/m^2 as the primary performance criterion rather than visual assessment of scaling as described in C672. The results shown in Fig. 12 and 13 are single tests on 300x300x75 mm slabs cast in a manner that allowed testing of a vertical plywood-formed surface representative of a pier or abutment or cast in standard manner to allow testing of either the top screeded surface or the bottom steel formed surface representative respectively of a finished deck or a formed beam soffit. Based on previous experience showing that salt scaling for top screeded surfaces is significantly greater than for bottom formed surfaces and the implication that fly ash concretes for this and other reasons are less suitable for decks than for other bridge components, the current testing program evaluated only vertical and bottom formed surfaces. The possibility that fly ash mixtures incapable of giving satisfactory scaling resistance with deicing salt might perform adequately in salt-free water was also explored since certain bridge components may offer a reasonable guarantee of freeze-thaw exposure without salt.

With respect to test surface, there is a consistent trend for vertically formed surfaces to scale more than bottom formed surfaces, likely to an extent intermediate between top screeded and bottom formed surfaces since the effect of bleeding is also intermediate between the extremes at top and bottom surfaces.

The significant adverse effect of deicing salt, 3% NaCl in this case, is clearly evident in the first series of tests where companion specimens were exposed only to water (Fig. 12, left). Both the 340 WN and 340 SP mixtures demonstrate a negligible tendency for scaling in water after slow cycle evaluation to 50 cycles, even up to 65% fly ash. However, for the same mixtures a tendency towards increased scaling after rapid cycling in water to 300 cycles, presumably a more severe testing regime, was noted at higher fly ash contents (Fig. 11), with the SP mixtures generally scaling less than corresponding WN mixtures. This suggests that there may be some merit to assessing resistance to scaling in water using the ASTM C666 procedure with weight loss converted to kg/m^2 of exposed surface.

For SU fly ash mixtures exposed to 3% NaCl solution there is clearly a marked increase in scaling as fly ash content increases, with 340 SP mixtures generally scaling less than 340 WN mixtures at the same fly ash content (Fig. 12, left). Increasing the cementitious material from 340 kg/m^3 to 420 kg/m^3 is also beneficial for SP mixtures of the same fly ash content (Fig. 12 right). These results appear consistent with previous work (ACI Concrete International, Vol. 16, No. 8, August 1994, pp. 48-55) that identifies *water-cement ratio*, w/c, and not water-cementing materials ratio as the primary governing parameter for scaling of properly air-entrained fly ash concretes. A w/c maximum of 0.45 is again shown as necessary to produce good scaling resistance (*good* is defined as less than 0.5 kg/m^2 in Swedish Standard SS 12 72 44).

For FG fly ash mixtures the marked increase in scaling with increase in fly ash content and consequently w/c is again apparent (Fig. 13), with SP mixtures again generally scaling less than WN mixtures of the same fly ash content (Fig. 13, left) and 420 SP mixtures scaling less

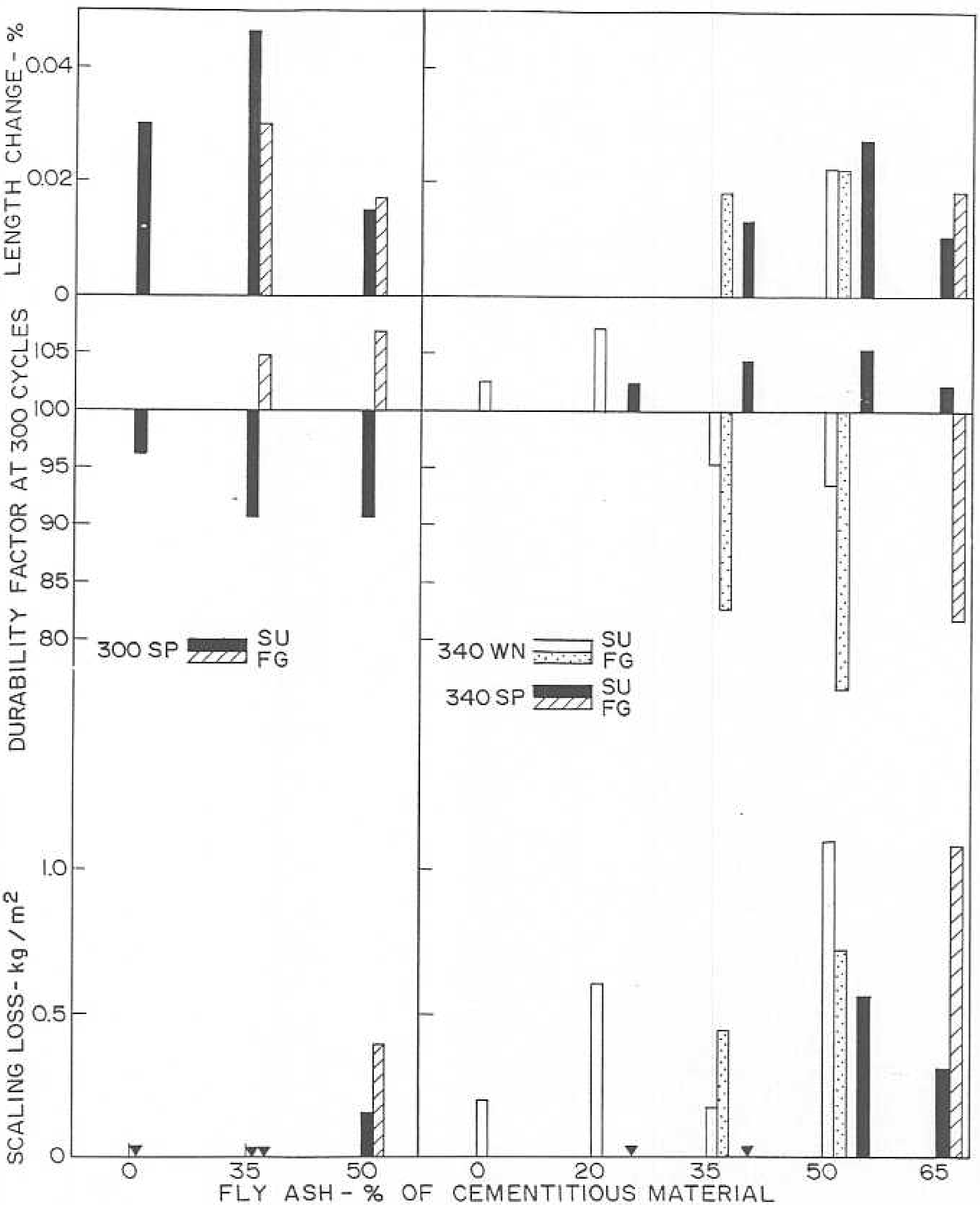

Fig. 11 Freeze-Thaw Performance in Water to 300 Cycles (ASTM C666, Procedure A)

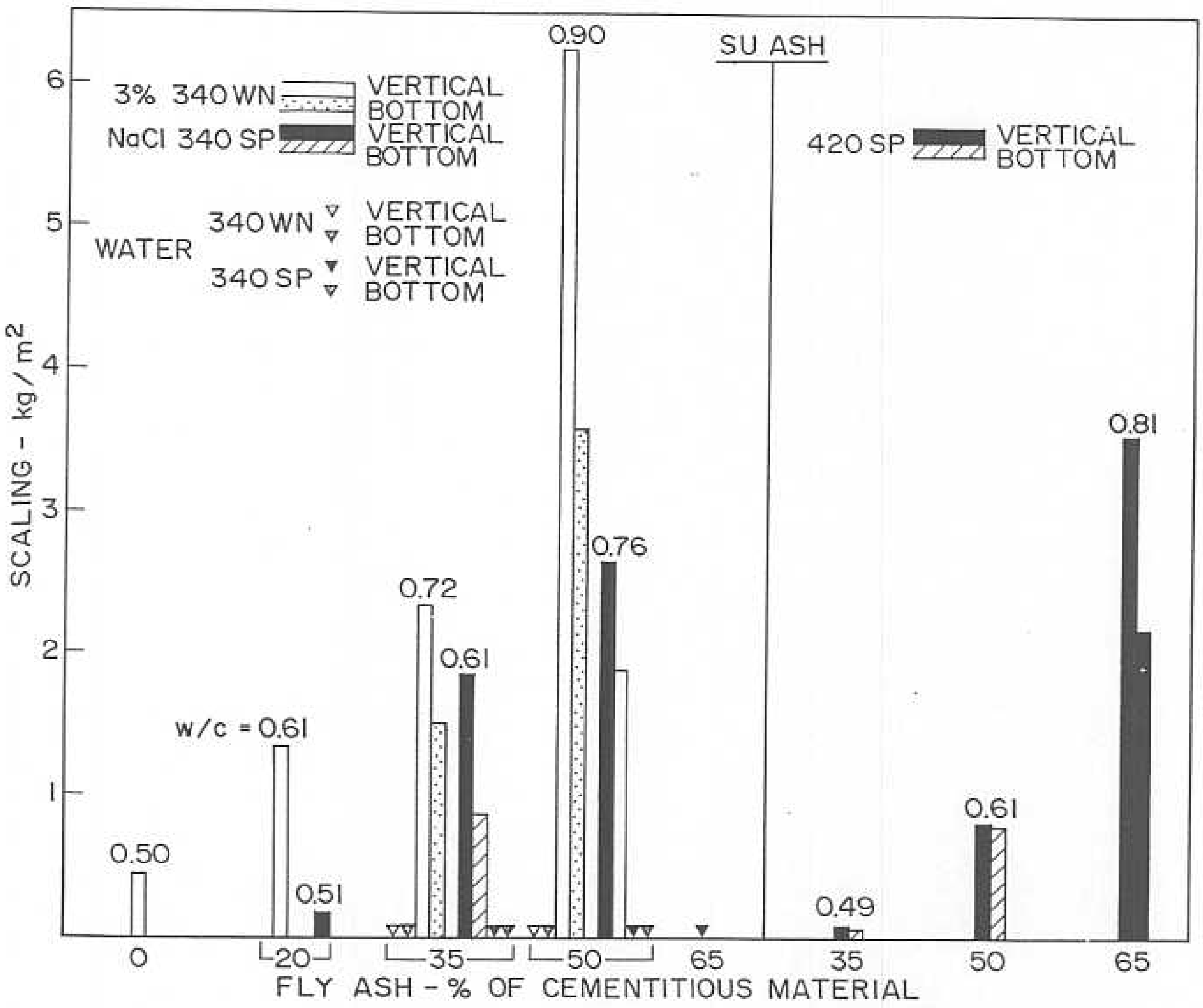

Fig. 12 Scaling of Sundance (SU) Fly Ash Concretes (Modified ASTM C672)

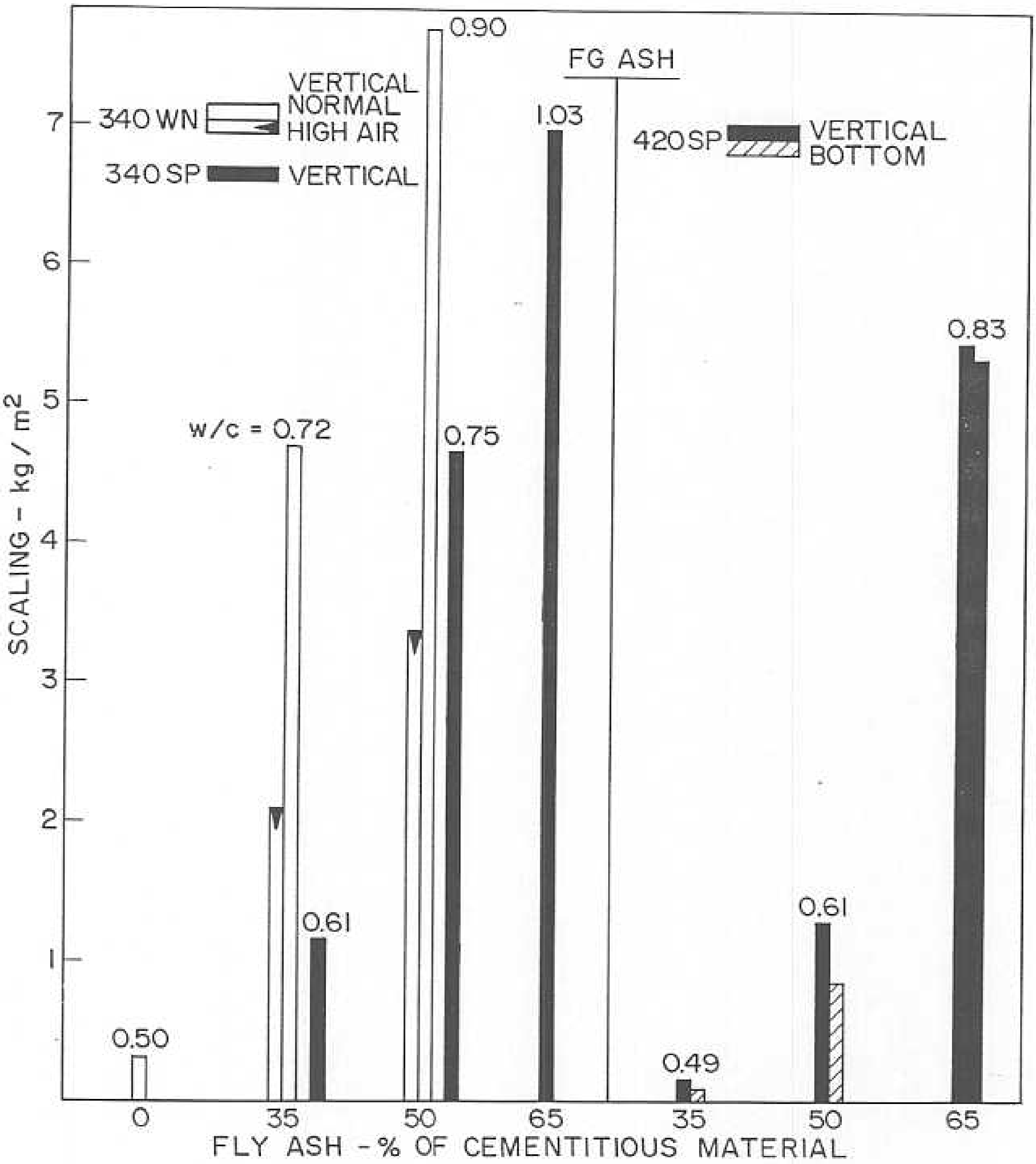

Fig. 13 Scaling of Foresburg (FG) Fly Ash Concretes (Modified ASTM C672)

than corresponding 340 SP mixtures of the same fly ash content. Comparing the degrees of scaling for corresponding mixtures with SU ash in Fig. 12, there is a fairly consistent tendency for the FG mixtures to scale somewhat more severely.

Several repeat tests on the same mixture depicted in Fig. 13 merit comment. The 340 WN mixtures with 35% and 50% fly ash coded 34 FG/35 and 34 FG/50 in Table 5 both had unusually high air content, at least 8.5% and possibly more according to their low strengths (Table 6), so they were repeated at a later date. The repeat mixtures, R34FG/35 and R34FG/50 in Table 5, had normal air comparable to other mixtures in the program. Yet, despite the very low strengths of 34 FG/35 and 34 FG/50 mixtures their "high air" seems to have produced better scaling resistance than the "normal air" equivalents (Fig. 13, left).

In another case of a repeat test, the 42FG/65 SP and R42FG/65 SP mixtures show about the same scaling despite a significantly higher strength for the latter mixture attributed to a 41% higher SP dosage. For the equivalent mixtures with SU ash, 42SU/65 SP and R42SU/65 SP, there is a difference in scaling but no other obvious difference between them other than an 18% higher SP dosage for the mixture with less scaling.

Clearly, many of the fly ash concretes evaluated are incapable of providing acceptable scaling resistance (defined as less than 1.0 kg/m^2 weight loss in SS 12 72 44 and 0.8 kg/m^2 by Ontario provincial standards) when exposed to 3% NaCl deicing salt. If w/c is the primary governing parameter in addition to proper air entrainment only a few mixtures relatively high in cementitious material and with relatively low percentages of fly ash, for example the 340 SP mixture with 20% SU ash and the 420 SP mixture with 35% of SU or FG ash, can produce acceptable scaling resistance. These tend to be relatively high in terms of both heat of hydration (Fig. 4) and cost equivalent (Fig. 9), so fly ash concretes offer more potential for bridge components which are naturally free of or can be protected from exposure to deicing salt. This limitation is probably the most important consideration to be recognized in drafting specification requirements that define the conditions under which fly ash may be used in bridge construction.

In this regard it should be emphasized that the currently permitted maximum of 0.45 for w/cm in CAN3-A23.1-M94 (Class C exposure) will in no way ensure satisfactory scaling resistance when using fly ash in the cm (cementing material). Only adherence to the historical limit of 0.45 on w/c in previous codes will do so (Fig. 12 and 13).

Electrical Indication of Resistance to Chloride Ion Penetration (ASTM C1202)

Often referred to as the rapid chloride permeability test, this test actually compares differences in electrical conductivity, which according to the standard have been found to correlate with resistance to chloride ion penetration for specimens with chloride ponded on the surface.

For the purpose of this investigation, the charge passed in coulombs is considered at least a relative indication of the probable effect of fly ash on resistance to chloride ion penetration and the consequent potential for chloride-induced corrosion of reinforcing steel. The results shown in Fig. 14 and 15 and enumerated in Table 9 are the average charge passed for two 95x102 mm cylindrical molded specimens calculated in accordance with C1202. Clearly, even at age 28 days a moderate amount of fly ash, as low as 35% of cementitious material, substantially reduces permeability. The additional benefit of using a superplasticizer is seen by comparing the 340 SP and 340 WN mixtures with 35% fly ash (Fig. 14 and 15 right). Further relatively smaller reductions are realized at higher fly ash levels of 50% and 65%, and as the concrete age increases to 90 days (Fig. 15). Once again, the results show a fairly consistent dependency on fly ash source with the SU ash tending to give slightly lower values than the FG ash.

In summary, under the conditions of ASTM C1202 fly ash even in quite small amounts tends to significantly improve resistance to chloride ion penetration, changing cement-only concretes that rate as moderate (> 2000) in chloride ion penetrability to concretes that rate very low (100-1000). Whether the improvement is realized to the same extent at low temperatures near the freezing point is questionable, and can only really be confirmed by tests which directly measure the chloride content at various depths in specimens such as those used in freeze-thaw scaling tests.

Shrinkage Potential (ASTM C157)

The results shown in Fig. 16 and enumerated in Table 9 are the average length change for pairs of 285x75x75 mm prisms moist-cured in lime water for 28 days and then dried at 50% relative humidity in accordance with ASTM C157. They clearly show that fly ash does not increase shrinkage potential and in most cases reduces it.

Shrinkage potential seems to depend on factors other than fly ash content when 340 WN mixtures with 0% and 50% fly ash are compared and when 340 SP mixtures with 35% and 65% fly ash are compared with each other or with the 420 SP mixture. The first obvious dependence involves the superplasticizer. Mixtures with SP shrink less than mixtures with WN admixture, regardless of fly ash content, probably in approximate proportion to their on average 16% lower water contents (Table 5). The second obvious dependence involves fly ash type. Mixtures with the SU ash show shrinkage on average 21% less than the corresponding mixtures with FG ash.

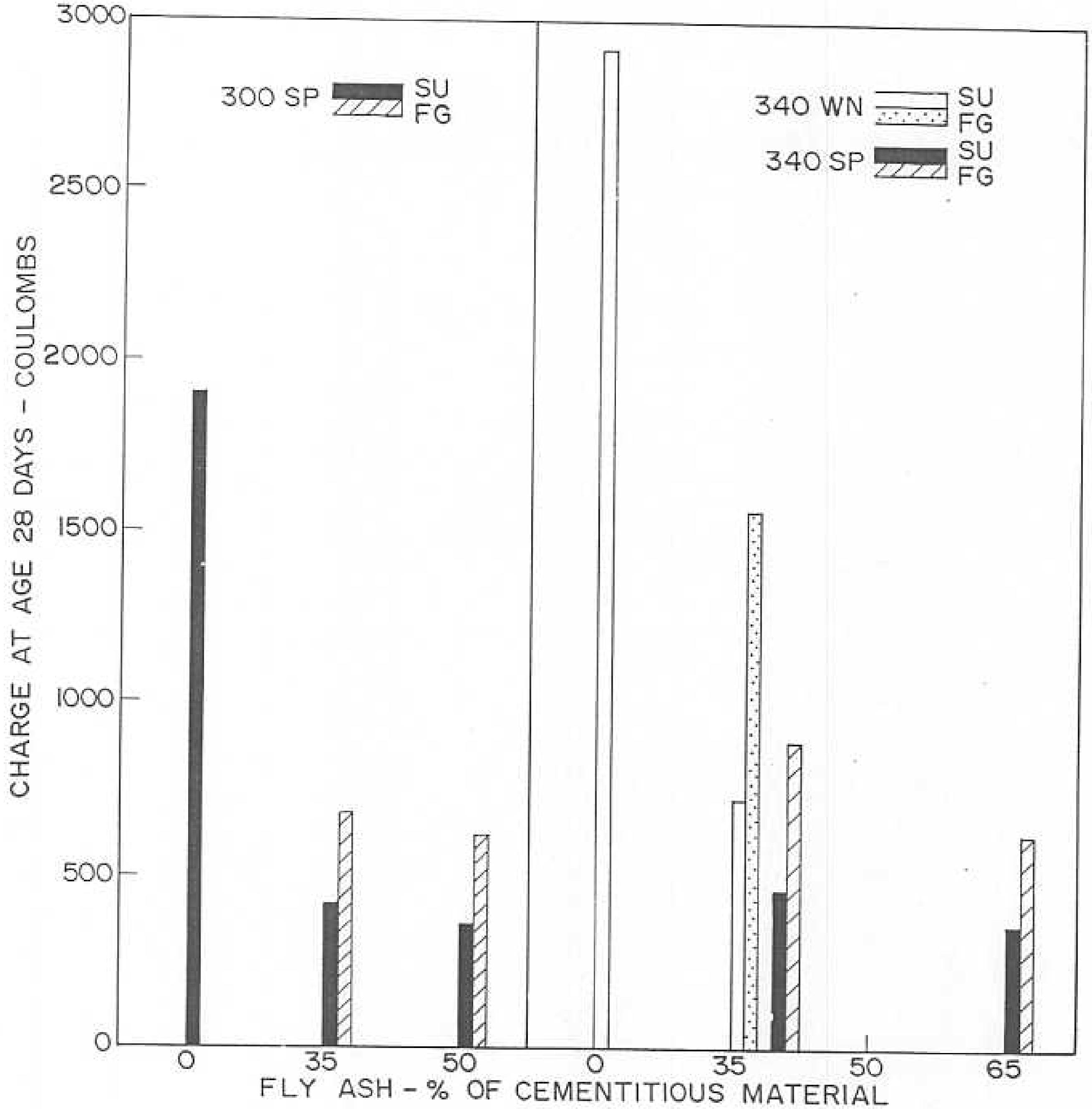

Fig. 14 Resistance to Chloride Ion Penetration at Age 28 Days (ASTM C1202)

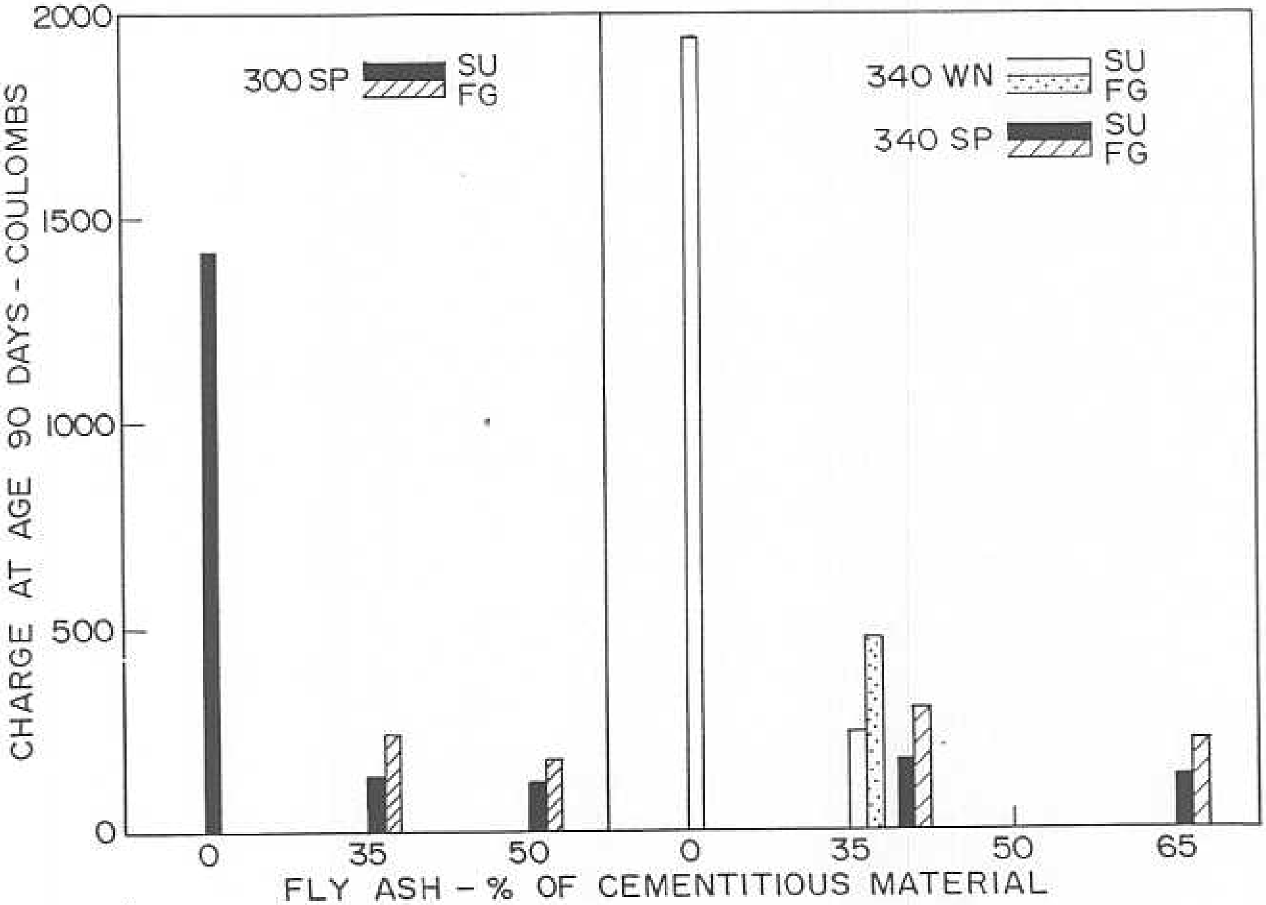

Fig. 15 Resistance to Chloride Ion Penetration at Age 90 Days (ASTM C672)

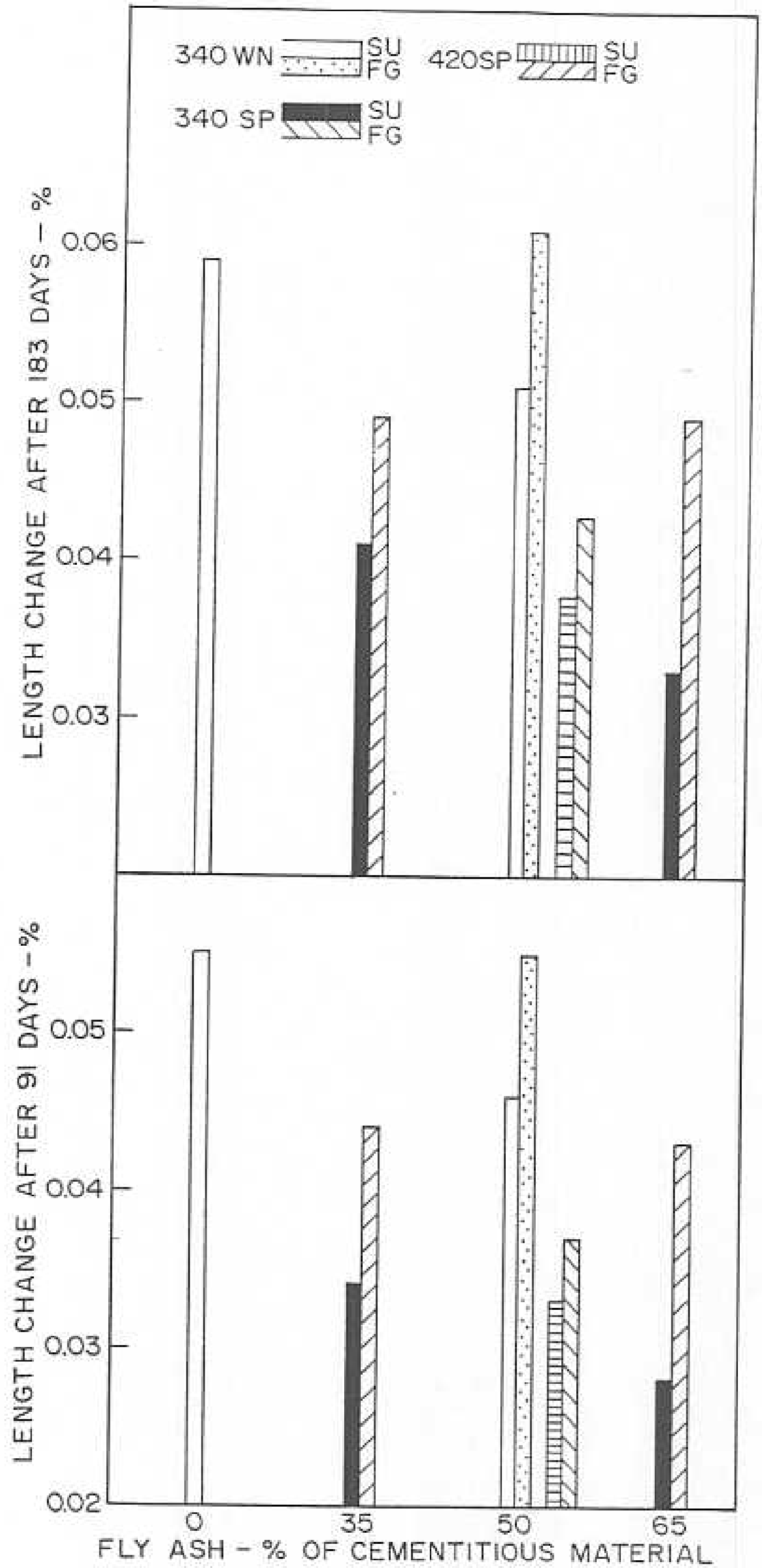

Fig. 16 Shrinkage Potential in Terms of Length Change of Concrete Prisms (ASTM C157)

In summary, fly ash does not tend to increase shrinkage potential and may be associated with reduced shrinkage potential in circumstances where its presence, or the presence of superplasticizer, or both, allow the water content to be reduced.

CONCLUSION

There are many potential advantages associated with using fly ash in air-entrained concrete for bridge works. They include reduced heat of hydration and the option to increase the specified strength or reduce the unit volume cost of the concrete, or some combination of both increased strength and reduced cost, all with the additional benefits of reduced electrical conductivity with respect to chloride ion penetration and in some circumstances reduced shrinkage potential. These benefits are much more effectively realized when a superplasticizing admixture is used instead of a conventional water-reducing admixture.

The main concern when using fly ash in the freezing and thawing conditions to which bridge components in Alberta are inevitably exposed hinges on whether deicing salts are likely to contact the concrete or not. The majority of fly ash concretes evaluated exhibit satisfactory durability under conditions of freezing and thawing saturated with salt-free water. Proper air entrainment coupled with the CAN3-A23.1-M94 requirements of 0.50 maximum for w/cm and a specified 28-day strength of 30 MPa seem to ensure satisfactory durability in ASTM C666 Procedure A which is generally considered to be more severe than any field exposure condition not involving deicing salt.

Most of the fly ash concretes evaluated do not offer satisfactory resistance to scaling in the presence of 3% sodium chloride solution. Only a minority characterized by a maximum *water-cement ratio* of about 0.45 with proper air entrainment can offer satisfactory resistance to freezing and thawing with deicing salt. This requires a relatively high cementitious material content of at least 420 kg/m^3, use of a superplasticizer, and a consequent limit of about 35% fly ash by weight of cementitious material. The CAN3-A23.1 limit of 0.45 for *water-cementing materials ratio* does not ensure satisfactory performance for deicing salt exposure.

The results on which these conclusions are based represent specific combinations of fly ash, air-entraining admixture and water-reducing or superplasticizing admixtures. They also indicate a degree of dependence on source of fly ash. Historically, fly ash variability between sources and even between samples produced at different times from a single source has been a concern limiting fly ash utilization, particularly in air-entrained concrete. Fly ashes considered for use in bridge works should be routinely monitored for uniformity in accordance with the procedures and requirements in ASTM C311, ASTM C618, and CAN3-A23.5, and should be evaluated with the admixture system, cement and aggregates to be used in the application considered.

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Table 1 - Schedule and Cost of Tests - Series I

Mixture Description					Summary of Tests Performed							
Code No.	Rep. %[a]	Cem. kg/m^3	Ash kg/m^3	Admix. System[b]	Heat & Strength[cde]	Freeze-Thaw		Setting Time[h]	Length Change[i]	Chloride Perm.[j]	Air Voids[k]	
						Scaling[f]	C666[g]					
34 SU	0	340	0	WN	x	1	x	x	x	2	x	
34 SU	20	272	68	WN	x	1	x					
34 SU	35	221	119	WN	x	4	x			2		
34 SU	50	170	170	WN	x	4	x	x	x		x	
34 SU	20	272	68	SP1	x	1	x					
34 SU	35	221	119	SP1	x	4	x		x	2		
34 SU	50	170	170	SP1	x	4	x	x			x	
34 SU	65	119	221	SP1	x	1*	x	—	x	2	x	
Number of tests					8	20	8	3	4	8	4	
Unit cost					350	310	300	120	170	180	270	Subtotal
Item costs-Series I					2800	6200	2400	360	680	1440	1080	$ 14,960
Schedule and Cost of Tests - Series II												
34 FG	0	340	0	WN	x	1						
34 FG	35	221	119	WN	x	1	x	x		2		
34 FG	50	170	170	WN	x	1	x	x	x			
34 FG	35	221	119	SP	x	1	x			2		
34 FG	50	170	170	SP	x	1		x	x		x	
34 FG	65	119	221	SP	x	1	x		x	2	x	
42 SU	35	273	148	SP	x	2						
42 SU	50	210	210	SP	x	2		x	x			
42 SU	65	148	273	SP	x	1						
42 FG	35	273	148	SP	x	2						
42 FG	50	210	210	SP	x	2		x	x			
42 FG	65	148	273	SP	x	1						
30 SU	35	195	105	SP	x		x			2		
30 SU	50	150	150	SP	x		x	x		2		
30 FG	35	195	105	SP	x		x			2		
30 FG	50	150	150	SP	x	—	x	x	—	2	—	
Number of tests					16	16	8	7	5	14	2	
Unit cost					350	310	300	120	170	180	270	Subtotal
Item costs-Series II					5600	4960	2400	840	850	2520	540	$ 17,710
												TOTAL
												$ 32,670

[a] - Percent fly ash by weight of total cementitious material.
[b] - All mixtures have air-entraining admixture (AEA) and either conventional water-reducer (WN) or superplasticizer (SP).
[c] - Including slump and air retention to conclusion of casting.
[d] - One 150 mm diameter cylinder insulated in styrofoam with temperature-measuring thermocouple for heat of hydration.
[e] - Five pairs of cylinders for compressive strength after 7, 28, and 90 days standard moist curing, limited moist curing followed by curing at 50% R.H. to age 28 days (simulative of site conditions without curing compound), or application of curing compound and curing at 50% R.H. to age 28 days (simulative of site curing with curing compound).
[f] - 300x300x75 mm slabs (area 0.052 m^2) with 3% NaCl or water tested using vertical or bottom-formed surfaces. Standard curing 14 days moist + 14 days at 50% R.H. Limited by freezer size to sets of 20 specimens per phase of testing. 1 signifies vertical surface tested with salt. 2 signifies vertical surfaces one tested with salt and one with water. 4 signifies vertical and bottom formed surfaces tested with both salt and water. 1* signifies vertical surface tested with water.
[g] - Pairs of 375x75x75 mm prisms to 300 cycles after 28 days moist curing.
[h] - Penetration resistance (ASTM C403) on mortar sieved from the parent concrete.
[i] - Pair of 285x75x75 mm prisms moist cured for 28 days prior to drying at 50% R.H. (ASTM C157).
[j] - Pairs of 50x100 mm cylinders tested by the electrical method (ASTM C1202) after 28 and 90 days moist curing for fly ash concretes, 28 days only for control mixture.
[k] - Microscopic air void analysis by modified point-count procedure (ASTM C457).

Table 2 - Coarse Aggregates[a]: Percentages Passing Standard Sieves

Sieve Size	28 mm	20 mm	14 mm	10 mm	5 mm	2.5 mm	Pan
28-14 mm gravel	100.0	71.8	9.2	0.5	0.2	0.1	0.0
14-5 mm gravel		100.0	95.7	53.2	3.4	0.1	0.0

[a] - Annualized 1990 data from Consolidated Concrete, Bearspaw Plant

Table 3 - Concrete Sand[a]: Percentages Passing Standard Sieves

Sieve Size	10 mm	5 mm	2.5 mm	1.25 mm	630 μm	315 μm	160 μm	80 μm	Pan
Sand	100.0	98.3	84.7	72.1	54.9	21.5	4.0	1.6	0.0

% < 80 μm = 1.61
Fineness Modulus: Mean 2.64, Range 2.50-2.80
[a] - Annualized 1990 data from Consolidated Concrete, Bearspaw Plan

Table 4 - Characteristics of Alberta Classified Fly Ashes[a]

Characteristic	Foresburg	Sundance	CAN3A23.5 Limits
Specific Gravity	1.92	2.02	-
Retained on 45 μm	31.9%	13.5%	34% max
Pozzolanic Activity } 7 days	79.3%	86.5%	68% min
with Cement } 28 days	86.8%	94.9%	75% min
Soundness (autoclave exp.)	0.07%	0.06%	0.8% max
SiO_2	59.5%	57.6%[b]	-
Al_2O_3	16.8%	25.0%[b]	-
Fe_2O_3	2.69%	3.79%[b]	-
$SiO_3 + Al_2O_3 + Fe_2O_3$	79.0%	86.4%[b]	70% min[c]
SO_3	0.20%	0.10%	5% max
CaO	9.36%	7.41%[b]	-
MgO	1.16%	0.88%[b]	-
Available Alkalies	1.71%	1.56%	-
Moisture	0.05%	0.03%	3% max
Loss on Ignition (LOI)	0.15%	0.33%	6% max

[a] - Annualized 1990 data from Inland Cement and Lafarge
[b] - Single test sample
[c] - ASTM C618 requirement

Table 5 - Proportions and Characteristics of Freshly Mixed Concrete

Mixture Code	Rep. %[b]	Cem. kg/m^3	Ash kg/m^3	Admix. System[c]	Slump mm	Water kg/m^3	Air-%[d] Initial	Air-%[d] Final(min)	Density[e] kg/m^3	AEA Dose[f] ml/100 kg
34 SU/00[a]	0	340	0	WN 300	46	170	5.5	-	2293	32 (2)*
34 SU/20	20	272	68	WN 300	54	166	7.7	-	2237	92 (3)*
34 SU/35	35	221	119	WN 300	63	160	7.7	-	2223	112 (2)*
34 SU/50	50	170	170	WN 300	58	154	6.3	6.0(36)	2237	240 (2)
34 FG/00[a]	0	340	0	WN 300	75	170	5.5		2308	22(1)*
34 FG/35	35	221	119	WN 324	71	160	8.7	8.7(51)	2166	309(1)
R 34 FG/35	35	221	119	WN 300	NR	156	6.5	5.8(34)	2237	110(1)
34 FG/50	50	170	170	WN 317	65	154	8.4	8.5(63)	2145	226(1)
R 34 FG/50	50	170	170	WN 300	80	154	6.5	6.0(43)	2237	113(1)
34/00 SP	0	340	0	SP 844	70	146	6.9		2315	173(2)
34 SU/20 SP	20	272	68	SP 1211	57	140	6.1		2308	140(3)*
34 SU/35 SP	35	221	119	SP 1029	76	135	6.3	5.6(45)	2301	303(2)
34 SU/50 SP	50	170	170	SP 1221	69	128	6.0	4.8(44)	2308	300(3)
34 SU/65 SP	65	119	221	SP 1046	105	122	6.7	5.4(28)	2265	258(2)
34 FG/35 SP	35	221	119	SP 1118	112	135	8.0	5.7(40)	2209	382(2)
34 FG/50 SP	50	170	170	SP 941	100	128	7.3		2209	338(2)
34 FG/65 SP	65	119	221	SP 1118	160	122	7.4	5.0(62)	2209	212(1)
42/00 SP	0	420	0	SP 699	62	151	5.2		2343	227(2)
42 SU/35 SP	35	273	148	SP 775	100	135	5.9		2308	459(2)
42 SU/50 SP	50	210	210	SP 754	115	128	8.2		2223	476(2)
42 SU/65 SP	65	148	273	SP 997	130	117	7.6		2230	714(2)
R 42 SU/65 SP	65	148	273	SP 1176	NR	122	6.9		2258	625(2)
42 FG/35 SP	35	273	148	SP 807	85	135	6.7	6.2(20)	2265	443(1)
42 FG/50 SP	50	210	210	SP 694	70	128	7.6		2237	456(2)
R 42 FG/65 SP	65	148	273	SP 1681	175	122	7.3		2237	595(1)
30/00 SP	0	300	0	SP 984	42	140	5.9	5.4(30)	2322	161(2)
30 SU/35 SP	35	195	105	SP 646	74	130	7.0	5.2(31)	2279	295(1)
30 SU/50 SP	50	150	150	SP 530	70	128	7.3	5.0(45)	2265	333(1)
30 FG/35 SP	35	195	105	SP 701	53	130	8.0	6.4(33)	2237	332(1)
30 FG/50 SP	50	150	150	SP 576	75	128	8.0	6.5(50)	2216	348(1)

[a] - Made about the same time as the following mixtures with SU or FG designation but without fly ash

[b] - Percent fly ash by weight of total cementitious material (340, 420, or 300 kg/m^3 in mixtures coded 34, 42, or 30 respectively)

[c] - WN denotes conventional water-reducing agent. SP denotes superplasticizer. Numbers denote dosage in ml/100 kg of total cementitious material

[d] - Air meter tests on freshly mixed concrete after mixing and at a later time denoted in minutes in parenthesis after the initial test following dosage adjustments to achieve required air

[e] - Density based on air meter sample in initial air test

[f] - Dosage with number of incremental additions in parenthesis. * signifies Microair. Otherwise MB AE 90 was used.

Table 6 - Characteristics of Hardened Concrete

Mixture Code	Heat of Hydration		Ratios		Compressive Strengths - MPa			Cost Equiv.[b] Cement-kg/m^3
	Max.-°C	Time-hr	w/c	w/cm	Actual & (Adjusted)[a] 7 days	28 days	90 days	
34 SU/00	48.7	20.5	0.50	-	28.4 (26.3)	35.0 (32.4)	39.0 (36.1)	340
34 SU/20	42.3	26.0	0.61	0.49	19.4 (20.1)	27.2 (28.2)	33.0 (34.2)	299
34 SU/35	39.6	26.5	0.72	0.47	16.5 (17.1)	28.1 (29.1)	32.2 (33.3)	269
34 SU/50	35.2	25.5	0.90	0.45	16.0 (15.4)	27.2 (26.2)	30.9 (29.8)	238
34 FG/00	45.4	22.4	0.50	-	29.0 (26.8)	37.4 (34.6)	43.7 (40.4)	340
34 FG/35	36.5	25.3	0.72	0.47	11.8 (12.8)	18.9 (20.5)	24.0 (26.0)	269
R 34 FG/35			0.71	0.46	22.1 (22.7)	31.1 (31.9)	40.0 (41.0)	269
34 FG/50	33.8	25.0	0.90	0.45	11.2 (12.0)	19.5 (20.9)	24.7 (26.4)	238
R 34 FG/50			0.90	0.45	15.0 (15.4)	25.7 (26.3)	32.4 (33.2)	238
34/00 SP	45.4	22.4	0.43	-	36.9 (36.7)	44.1 (43.9)	49.5 (49.3)	340
34 SU/20 SP	41.9	21.5	0.51	0.41	31.4 (30.0)	43.4 (41.4)	51.8 (49.5)	299
34 SU/35 SP	38.7	22.0	0.61	0.40	26.0 (25.1)	39.8 (38.4)	43.1 (41.6)	269
34 SU/50 SP	34.7	23.0	0.76	0.38	26.9 (25.6)	39.7 (37.7)	47.9 (45.5)	238
34 SU/65 SP	30.9	25.5	1.03	0.36	20.6 (20.3)	36.2 (35.7)	43.5 (42.8)	207
34 FG/35 SP	37.1	23.1	0.61	0.40	24.5 (25.7)	37.0 (38.9)	43.9 (46.1)	269
34 FG/50 SP	33.4	23.0	0.75	0.38	18.4 (18.7)	30.1 (30.6)	39.8 (40.4)	238
34 FG/65 SP	29.6	26.5	1.03	0.36	15.2 (15.5)	28.9 (29.5)	38.8 (39.6)	207
42/00 SP	51.0	22.4	0.36	-	40.7 (37.0)	46.5 (42.3)	54.8 (49.9)	420
42 SU/35 SP	43.3	25.8	0.49	0.32	28.9 (27.3)	49.4 (46.7)	55.3 (52.3)	332
42 SU/50 SP	38.9	27.4	0.61	0.31	31.2 (31.5)	47.0 (47.5)	49.0 (49.5)	294
42 SU/65 SP	34.1	33.7	0.79	0.28	25.4 (26.2)	42.2 (43.5)	45.4 (46.8)	257
R 42 SU/65 SP	35.9	29.8	0.83	0.29	30.4 (30.2)	46.6 (46.4)	54.2 (53.9)	257
42 FG/35 SP	42.6	25.8	0.49	0.32	28.9 (28.5)	42.1 (41.5)	49.4 (48.7)	332
42 FG/50 SP	38.7	25.7	0.61	0.31	25.7 (26.5)	37.1 (38.2)	43.3 (44.6)	294
R 42 FG/65 SP	34.8	29.3	0.83	0.29	24.2 (24.6)	41.0 (41.6)	53.2 (54.0)	257
30/00 SP	42.6	20.8	0.47	-	35.7 (33.7)	42.0 (39.7)	?	300
30 SU/35 SP	37.8	25.5	0.66	0.43	23.8 (23.8)	39.0 (39.0)	43.0 (43.0)	237
30 SU/50 SP	33.4	26.2	0.85	0.43	19.8 (20.1)	30.7 (31.2)	38.4 (39.0)	210
30 FG/35 SP	37.8	22.9	0.66	0.43	20.7 (21.7)	32.3 (33.9)	39.4 (41.4)	237
30 FG/50 SP	33.3	22.0	0.85	0.43	14.8 (15.5)	24.8 (26.0)	34.0 (35.7)	210

[a] - Adjusted to 7% air content on basis of 5% change in strength per 1% change in air content

[b] - Fly ash at 40% cost of cement

Table 7 - Effect of Curing Conditions on Strength Development

Mixture Code	Strength Reductions -% for Days of Dry (D) Curing (50% R.H.) or Days with Curing Compound (CC)							Reference[a] Strength-MPa
	3M/25D	5M/23D	7M/21D	1M/27CC	3M/25CC	5M/23CC	7M/21CC	
34 SU/00	3.7			7.7				35.0
34 SU/20	12.0			19.9				27.2
34 SU/35	13.5			34.5				28.1
34 SU/50	16.9			34.8				27.2
34 FG/00	3.2				1.5			37.4
34 FG/35	20.1				12.6			18.9
R 34 FG/35	13.0				14.4			31.1
34 FG/50	21.1				23.5			19.5
R 34 FG/50	19.6				18.8			25.7
34/00 SP	-6.3							44.1
34 SU/20 SP	6.5			10.1				43.4
34 SU/35 SP	11.0			17.6				39.8
34 SU/50 SP	1.9			21.4				39.7
34 SU/65 SP	16.0			38.1				36.2
34 FG/35 SP	12.0				12.5			37.0
34 FG/50 SP	9.0				10.1			30.1
34 FG/65 SP	17.7				19.3			28.9
42/00 SP		-7.0				-7.7		46.5
42 SU/35 SP		-0.9				-4.2		49.4
42 SU/50 SP		1.7				0.1		47.0
42 SU/65 SP		1.9				4.7		42.2
R 42 SU/65 SP		-1.0				-1.1		46.6
42 FG/35 SP		0.0				-3.3		42.1
42 FG/50 SP		0.0				-2.4		37.1
R 42 FG/65 SP		8.4				9.0		41.0
30/00 SP			-10.5				-8.4	42.0
30 SU/35 SP			-0.2				-1.4	39.0
30 SU/50 SP			-8.8				-5.4	30.7
30 FG/35 SP			-1.4				-1.4	32.3
30 FG/50 SP			0.9				1.7	24.8

[a] - 28 days of standard moist curing

Table 8 - Freeze-Thaw Durability and Air Void Parameters

Mixture Code	Rapid F/T (ASTM C666)			Scaling Losses - kg/m²				Air Void Parameters			
	Durability Factor	Scaling kg/m²	Length Change-%	3% NaCl		Water		Air[a] %	Air[b] %	α mm^{-1}	$\bar{L}$ mm
				Vertical	Bottom	Vertical	Bottom				
34 SU/00	102.4	0.20		0.43					4.1	27.6	0.20
34 SU/20	107.1	0.60		1.33							
34 SU/35	95.2	0.17		2.33	1.50	0.0	0.0				
34 SU/50	93.5	1.10	0.022	6.24	3.57	0.002	0.002	6.0	6.1	21.3	0.21
34 SU/20 SP	102.2	0.00		0.17							
34 SU/35 SP	104.1	0.02	0.013	1.84	0.93	0.002	0.002	5.6			
34 SU/50 SP	105.1	0.56	0.027	2.62	1.88	0.0	0.0	4.8	5.7	16.1	0.29
34 SU/65 SP	102.1	0.30	0.010			0.015		5.4	6.1	13.6	0.33
34 FG/00				0.29							
34 FG/35	82.7	0.44	0.018	2.08				8.7			
R 34 FG/35				4.68				5.8			
34 FG/50	75.8	0.72	0.022	3.35				8.5			
R 34 FG/50				7.67				6.0			
34 FG/35 SP				1.13				5.7			
34 FG/50 SP				4.63					6.6	14.6	0.31
34 FG/65 SP	81.7	1.08	0.018	6.95				5.0	4.9	16.8	0.28
42 SU/35 SP				0.09	0.06						
42 SU/50 SP				0.80	0.79						
42 SU/65 SP				3.53							
R 42 SU/65 SP				2.17							
42 FG/35 SP				0.14	0.08			6.2			
42 FG/50 SP				1.28	0.84						
42 FG/65 SP				5.42							
R 42 FG/65 SP				5.31							
30/00 SP	96.2	0.00	0.030					5.4			
30 SU/35 SP	90.9	0.04	0.046					5.2			
30 SU/50 SP	90.8	0.15	0.015					5.0			
30 FG/35 SP	104.8	0.00	0.030					6.4			
30 FG/50 SP	106.9	0.39	0.017					6.5			

[a] - Air meter final reading at or near end of casting
[b] - Modified point-count (ASTM C457)

Table 9 - Chloride Permeability and Shrinkage Potential

Mixture Code	Charge-coulombs[a]		Length Change-%[b]	
	28 days	90 days	91 days	183 days
34 SU/00	2910	1938	0.055	0.059
34 SU/35	718	241		
34 SU/50			0.046	0.051
34 SU/35 SP	457	171	0.034	0.041
34 SU/65 SP	378	132	0.028	0.033
34 FG/35	1564	470		
34 FG/50			0.055	0.061
34 FG/35 SP	885	301	0.044	0.049
34 FG/65 SP	616	214	0.043	0.049
42 SU/50 SP			0.033	0.038
42 FG/50 SP			0.037	0.043
30/00 SP	1903	1408		
30 SU/35 SP	419	141		
30 SU/50 SP	357	121		
30 FG/35 SP	679	241		
30 FG/50 SP	623[c]	181		

[a] - Electrical indication of resistance to chloride ion penetration (ASTM C1202)
[b] - Shrinkage after drying at 50% relative humidity following moist curing to age 28 days
[c] - Single result