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The efficient and effective use of portland cement in ready-mix concrete is a principal economic factor to both the producer and the consumer. Concrete is by far the most widely used and versatile manufactured construction material employed in Canada's largest industry; the bulk of this concrete is supplied by the ready-mix producer. Although portland cement is the least expensive major industrial chemical, it is almost invariably the most costly ingredient in concrete.

Portland cement is a complex chemical manufactured under highly controlled conditions made necessary by the basic requirements of soundness and strength development properties. It is a product whose properties vary considerably. Because this is also the case with aggregates and admixtures, a prime concern of the ready-mix producer is to supply job concrete of uniform properties.

Today's wider use of concrete and refinement in construction methods have led to demands for greater modifications in the properties of portland cement concrete which often requires the use of modified cements. Architectural concrete demands colour and texture uniformity; exposed concretes must withstand severe environmental conditions such as sulphate attack, freeze-thaw and de-icing salt deterioration, and seawater attack. Special cements are required where alkali-reactive aggregates must be used. The finishing characteristics of concrete depend greatly on cement characteristics.

The ready-mix producer occupies a unique position among manufacturers in that he performs only the first part of the manufacturing process, i.e. the production of the plastic mix. He has no control over the remaining critical operations of placing, compacting, finishing, and curing, yet he must accept responsibility for the final product. He must also be able to meet the individual requirements of several jobs at one time.

In this situation the ready-mix producer must maintain optimum control over his methods of and facilities for manufacturing, of which the selection and control of concrete ingredients are of primary importance. This paper examines these problems as they relate to the portland cement component.

COMPLEXITY IN CEMENT MANUFACTURE

The basic chemical components required for the manufacture of portland cement are lime and silica derived from quarries and pits of limestones, shales, sands, and clays. For economic reasons variable minor components are, and can be, tolerated within certain limits. Among them are alumina and iron oxide which, although undesirable in several respects, serve as useful fluxes in the clinkering process. One might therefore expect cements from different plants to have essentially the same major components but vary considerably in minor components. Even in the same quarry there will be variations in such raw materials.

The mineralogical differences in raw materials will result in variations in grindability and burnability thus affecting the clinker properties. Blending of the milled kiln feed before burning is an important process as the homogeneity of raw mix determines smoothness of burning process and, therefore, uniformity of clinker. Modern methods such as computerized control of raw mix and television-view control of burning have done much to improve the uniformity of clinker.

Clinker storage normally provides for a cooling and blending procedure necessary to quality and uniformity of the cement product. Protection from excessive weathering is still a problem, not so much because of deterioration in strength properties but because of the variations in such properties that can result. Blending clinker by such means as simultaneous withdrawal from several ports in the storage area is now considered good practice.

Grinding hot clinker is detrimental to the cement. Partial dehydration of the gypsum component produces false-setting properties; "hot cement" causes problems in normal setting of concrete. Uniform gypsum addition during milling of clinker can be difficult if this material has become caked during storage.

After milling, the cement may be blended or sent directly to storage silos. Modern plants generally use air-lift methods to move the cement. Varying relative humidities can affect the amount of aeration, carbonation, and prehydration, to a degree that is usually of importance only if a cement is subjected to two or more air-lifts before use. False-setting properties of cement are often aggravated by aeration.

There is good reason for a user of portland cement to become familiar with these basic manufacturing processes as well as the particular practices of his supplier.

SIGNIFICANCE OF CEMENT COMPOSITION

Chemical and Mineralogical

The main chemical components of portland cement have the following ranges: 60-70 per cent CaO (lime), 17-25 per cent SiO_2 (silica), 3-8 per cent $A\ell_2O_3$ (alumina), 0.5-6.0 per cent Fe_2O_3 (iron oxide), 0.1-5.0 per cent MgO (magnesia), 0.5-1.3 per cent $Na_2O + K_2O$ (alkalis), and 1-3 per cent SO_3 (derived from gypsum).

A typical ordinary portland cement (ASTM Type I) may have the following composition:

Chemical Analyses				Calculated Compound Composition (mineralogical)			
CaO	-	64.9	per cent	C_3S	-	41	per cent
SiO_2	-	24.0	per cent	C_2S	-	38	per cent
$A\ell_2O_3$	-	4.0	per cent	C_3A	-	7	per cent
Fe_2O_3	-	2.1	per cent				
SO_3	-	1.7	per cent	C_4AF	-	6	per cent
MgO	-	1.9	per cent	Free C (CaO)	-	1.5	per cent
Na_2O	-	0.23	per cent	C = CaO			S = SiO_2
K_2O	-	0.55	per cent	A = $A\ell_2O_3$			F = Fe_2O_3

C_3S and C_2S (tri- and dicalcium silicates) are the desired major compounds of portland cement and together account for some 75-80 per cent of the total weight. They hydrate in water to form calcium silicate hydrates which, in the hardened state, form the rigid solid paste whose strength and low permeability are familiar. C_3S contributes mainly to early strength whereas C_2S is responsible for later strength gains. The proportion of C_3S is usually limited to avoid increased difficulty and cost of burning.

C_3A (tricalcium aluminate) also contributes to early strengths but is undesirable because of early heat generation, vulnerability to sulphate attack, and other factors. The C_4AF component (tetracalcium aluminoferrite) makes no useful contribution but has no significant adverse effect either except that of dilution. The C_4AF with the C_3A derives from the fluxing materials $A\ell_2O_3$ and Fe_2O_3 which are normally present in the original raw materials. As more Fe_2O_3 is used it combines with C_3A to form C_4AF; this is, therefore, the usual method of obtaining low-C_3A cements (low heat and sulphate resistant).

The CaO (free lime) is the residue of lime left uncombined in the clinkering process. In amounts less than ±2 per cent, it indicates that the compounds, C_3S, C_2S, C_3A and C_4AF, are formed as calculated. If the free lime is high the cement is unsound in which case excessive expansion and deterioration will occur in mortars and concretes. The autoclave test is used to determine the soundness of a portland cement.

The SO_3 (sulphur troxide) represents the gypsum ($CaSO_4 . 2H_2O$) purposefully added during the grinding of the clinker. A small part of the SO_3 may, however, be present in the original clinker. The function of the gypsum is to control both initial and final setting times; insufficient amounts may lead to flash setting. Partial dehydration during grinding with clinker may lead to false-set properties while too much gypsum may produce excessive expansion. Optimum amounts are desirable for other reasons such as maximum strength and minimum drying shrinkage of the paste.

The MgO (magnesia) is undesirable but is inevitably present as an impurity. It is restricted because of the danger of delayed expansion of mortars and concretes due to its slow hydration to $Mg(OH)_2$ (brucite). Alkalis (Na_2O + K_2O) are also undesirable because of a danger of alkali-aggregate reaction, the development of efflorescence, or excessive rates of setting in hot weather.

Standards for Chemical Requirements

Despite the variations that are possible in chemical and mineralogical composition, the Canadian Standards Specification A5-1961 (with revisions to 1968) imposes very few limits as is shown in Table I. This Specification, as is also the case with ASTM C-150, is designed to insure a minimum quality portland cement. It is not designed to provide for a uniform product. If uniformity is an important requirement, a user's specification should include, in addition to the CSA minimum requirements, both upper and lower limits on relevant properties.

The maximum loss on ignition of 0.3 per cent indicates that if this value is exceeded, the cement has suffered excessive exposure to moisture (prehydration) and carbon dioxide (carbonation). Insoluble residue limits are designed to insure that the proper chemical combinations took place in the burning process. The SO_3 limits are varied in accordance with the C_3A content because these two components combine during hydration processes and affect both setting time and strength. In sulphate-resistant cements, the C_3A is limited to a low value because it is the component vulnerable to sulphate attack; consequently, less gypsum is needed (SO_3).

It is clear that these standards (for quality) are not adequate enough to insure uniformity of properties for a continuous user of cement, i.e., a ready-mix producer. For his purposes he might require his cement supplier to meet both minima and maxima requirements for certain compositional properties, e.g., C_3A. He might also find it necessary to specify limits on heat of hydration when a special low heat cement is required for mass concrete.

Compositional Tests

Well established analytical methods exist for determining any or all of the compositional properties of portland cement. Most of these are used by the cement manufacturer on a routine basis for control purposes, and to insure good, competitive quality. Results are readily available to the purchaser.

PHYSICAL PROPERTIES, SPECIFICATIONS AND TESTS

Of concern to the user of portland cement are the physical properties of each of the three separate states: the dry cement, the plastic condition, and the hardened state.

The Dry Cement

(a) CSA - A5-1961 (Table II, revised to 1968) has only one requirement: for fineness, a maximum of 18 per cent retained on a 200-mesh sieve for normal portland and sulphate resistant cements. As there is no minimum limit, this "one-side limit" provides only for quality, not for uniformity. This property is of primary importance in strength development.

No limits are placed on such important properties of dry cement as specific surface (ASTM C150 uses this instead of sieve value), temperature, colour, and pack-set properties. This also applies to heat of hydration, a chemical property often listed in physical requirements. Established methods of test are available for these properties and they are usually carried out on a routine basis by cement producers.

It is to be emphasized that a good specification should be so designed as to interfere as little as possible with freedom of manufacturing procedures. Thus, properties not normally limited may require separate user specifications when warranted.

(b) A severe pack-setting cement may pose serious problems of withdrawal from cement silos and from transport trucks. A free-flowing cement is produced by some cement plants by incorporating an additive (usually an acetate derivative) during clinker grinding with gypsum.

(c) "Hot cement" results from grinding uncooled clinker, and is usually a problem during heavy demands for cement. It has adverse effects on water-requirements of concrete, on air-entrainment properties, on slump control, on rate of setting, and is conducive also to false-set properties. This property is easily detected.

(d) Uniformity of colour is of importance in architectural concretes. Variation from plant to plant can be expected because of differences in the minor components of raw materials. Even with the same components variations in kiln burns may affect the colour. Slight changes in proportions of raw materials can also produce variations in colour. Tests to determine colour uniformity can readily be done on a routine basis.

(e) Testing for specific surface, usually by the Blaine method, is carried out routinely in cement plants as part of quality control. User specifications might well specify both upper and lower limits to insure added uniformity not only of strengths, but also of properties associated with air-entrainment, slump, and rate of stiffening.

The Plastic State

(a) CSA - A5 standards place "one-side limits" only on initial and final setting times of portland cements. Setting properties are now assuming more importance because of the special requirements necessary for cold weather concreting and control of construction joints in certain concrete elements, and also because of the extensive use of set-retarding and water-reducing admixtures. Thus, "two-side limits" may be required under certain conditions.

CSA - A5 does not place limits on such properties of the plastic state as false set, water requirement, bleeding, and specific admixture effects, but methods of test are available and cement plants often carry out some or all these tests on periodic bases. Some cement users find it necessary for their purposes to set their own specifications for one or more of these properties.

(b) Water-requirement to produce a "normal consistency" of cement paste is important to several properties of the concrete: slump control, strength, air-entrainment, and rate of stiffening. Variations in this property can be traced to variations in composition and burning of the clinker, and also to variations in specific surface of the cement. Uniformity of this property can readily be followed from the routine quality control test results in any cement plant.

(c) The bleeding characteristics of portland cement, of critical importance in finishing operations, also have an important bearing on strength of the concrete. This property of the cement, along with such contributing factors as type of admixture and nature of aggregate, can significantly affect the yield of concrete which is an important consideration to both producer and user of concrete.

Variations in bleeding properties are traceable to variations in specific surface of cement, variations in nature of clinker as affected by burning, and the nature of additives used in grinding the clinker. Cement plants usually carry out this test as routine.

(d) The false-setting phenomenon occurs sporadically, yet often enough to be considered a chronic problem. It can happen without warning in spite of the generally accepted explanation that it is the result of partial dehydration of the gypsum caused by excessive temperatures during milling of the clinker. Control during manufacture involves one or more of the following: avoiding high grinding temperatures; use of anhydrite as a partial replacement for the gypsum component; and, limiting the number of air-lift operations. The latter has been shown to aggravate false-set problems, apparently through a combination of hydration and carbonation. One ready-mix producer has observed that a cement may be subjected to as many as six air-lifts before getting into the concrete.

Because false set is aggravated by increasing fineness of grind, it is more common in high early strength cements. One characteristic of this property is that it can be destroyed by prolonged mixing. consequently, it is not as serious in transit-mix concrete as it is in the premix type. Most cement users place limits on false set, and most cement plants use established methods to check this property as a routine procedure. False set should not be confused with flash set; the latter is usually caused by a deficiency of gypsum and is thus the result of an error in milling.

(e) The effect of admixtures on paste properties can be variable particularly with respect to different brands and dosages. Some cements respond more favourably than others to a given admixture, a specific example being the effect of calcium chloride on setting and bleeding properties. Chemical set-retarders, even in normal dosage, may induce excessive delay in setting, especially with cements low in C_3A and alkalis. The solutions to this problem lie in limiting the number of admixtures used as well as in uniformity of both cement and admixture. Again, test methods are available and are not difficult to carry out.

The Hardened State

(a) Properties of the hardened state, as of the plastic condition, are directly related to performance of concrete and CSA - A5 specifications are somewhat more restrictive. "One-side limits" are placed on autoclave expansion, compressive strengths, and on expansion for sulphate-resistant cements. No limits are placed on drying shrinkage, colour, or specific admixture effects.

(b) The autoclave expansion test is a basic test for soundness, i.e., proper combination of the components of raw mix during burning of clinker. It is a routine test in the cement plant. The sulphate resistance test is also easily carried out as routine for such cements.

(c) Of the properties not limited by CSA - A5 standards, the drying shrinkage characteristics are sometimes of critical importance. Variables are associated with composition and burning of clinker, and with gypsum content. Test methods are established, and data may be made available on a routine basis if required. Colour may be affected by other concrete ingredients and by mix composition; hence, it may be checked on the hardened state of concrete. Response to admixtures in the hardened state can also be variable, e.g., strength gains with the accelerator calcium chloride. Uniformity of both cement and admixture must be controlled.

(d) The primary concern of the cement user is usually the strength characteristics of the cement. Variations in this property make it difficult, and often costly, to maintain uniformity of concrete strengths frequently required by large projects. These variations occur not only from plant to plant for one type of cement, but even occur within a given plant, often on a seasonal basis. Much research has been and is now being done to reduce such variations, the causes of which are traceable to the complexity in the manufacturing and handling operations discussed previously.

As an example, one ready-mix producer found, under laboratory test conditions, that the concrete made with one of two successive shipments of a cement from the same plant required six per cent more water than the other to produce the same slump. The resulting effect on strengths was correspondingly large.

Bad competitive practices can lead to gross differences in cement strengths from time to time and from place to place. A classic example is the difference between ordinary portland cement strengths, at 28 days, in western and eastern Canada; about 5500 psi as compared with about 4500 psi respectively - a remarkable situation. On the other hand, in eastern Canada the strength differences at early ages, 3 and 7 days, have varied by as much as 100 per cent for Type I. Apart from the unfavourable economic effects of such industrial competition on the manufacturers, the user also suffers not only because of lack of uniformity but because the excessively rapid strength gains of some of these cements can be damaging to concrete quality.

Present indications are that this variation in cement strengths cannot be eliminated except by a blending procedure worked out between the supplier and user of the cement. Progress can be made in solving this problem by the active participation of the producer and the consumer of cement in existing CSA committees which do set up specifications and can, therefore, develop recommended practices. Much can be done in the area of continuous liaison with cement plant laboratories, particularly with regard to changes in trends in properties of cement. Reasonable specifications can be developed to provide for uniformity of product by requiring upper as well as lower limits on strength.

TYPES OF PORTLAND CEMENT

Modern construction procedures have become so diversified and applications of concrete so extended that the normal performance characteristics of concrete often have to be modified. Such changes can be brought about by modifying the mix, e.g., using one or more admixtures, or using a different type of cement. Normal portland (ASTM Type I) still meets the need for most construction work.

High early strength portland cement (ASTM Type III) is usually made from the same clinker as Type I but is ground to greater fineness (5000 Blaine as against about 3200 Blaine). Some plants find it necessary also to raise the C_3S or C_3A content, or both, and therefore must produce a separate clinker. Because of this one must expect considerable variation from mill to mill.

These rapid hardening cements are used in such cases as precasting, cold weather construction, and where early removal of formwork is required. They differ in some important respects from ordinary portland in their effects on plastic and green concrete - showing a greater tendency to false setting, producing a greater temperature rise, and usually exhibiting greater drying shrinkage. They require some adjustment therefore in mix designs and in handling and placing practices. The common alternative to high early portland is the use of calcium chlorides with normal portland cement, a somewhat less effective method and one often prohibited where reinforced or prestressed concrete is involved.

Some Canadian cement companies manufacture a portland cement intermediate in fineness between the normal and the high early type. It is made by grinding a Type I clinker to about 4000 Blaine. Although produced originally for block and other precast manufacture, it is often used in ready-mix for special requirements. As might be expected there is generally a cost difference between cements of differing fineness.

Low heat cements (low in C_3A and usually low in C_3S) are used in mass construction where early temperature rise must be kept low to avoid cracking. Aids or alternatives are precooled concrete (using ice) or pozzolan replacements for part of the cement. Fly ash is now used in parts of Canada to prevent early temperature rise as well as for workability and economic reasons. Mineral powder admixtures (fly ash or other pozzolan) should be used with caution, however, because of the reduction in early strengths and the increase in permeability of the leaner concretes.

Sulphate-resistant cement (ASTM Type V, low in C_3A) is well known and widely used in western Canada where the problem of sulphate attack is fairly general. Low alkali cements are manufactured, on order, where alkali-expansive aggregates are used (in some Nova Scotia concreting).

Where a ready-mix operator is sometimes required to supply types other than normal portland, he faces not only the problem and costs of extra storage space and facilities but also the problem of disposing of the residue of such special portland cement types. The usual practice is to blend small quantities of these special cement types with normal portland. This is not bad practice providing: (a) the special cement is one of the portland types already noted; (b) only small proportions (e.g., 5 per cent) are used at one time; (c) blending is efficient; (d) it be used only in concretes for footings or massive subfloors; and (e) the consumer is informed of these provisions.

FURTHER PRACTICAL CONSIDERATIONS

Strengths

The relation between strength of cement as determined on the standard two-in. mortar cube and the strength of the concrete as determined in the 6- by 12-in. concrete cylinder is not a direct one. In fact, the variability is such that a simple conversion factor for the same cement type cannot be relied upon, even if the cement derives from the same plant. Studies are being undertaken on a major scale by one Canadian cement company to try and obtain better correlation.

The continuing emphasis on compressive strength as the main specification requirement points to the importance of developing, in the ready-mix plant, a concrete cylinder test system that will provide precise information on performance of the cement component. This is of particular importance in developing relationships between 3-, 7- and 28-day strengths that can be used to check on the variability of the cement in the matter of strength development.

The lack of correlation between the cylinder strengths, made under field or laboratory conditions, and the concrete cores from the hardened concrete in the structure is familiar to the ready-mix producer. The strength characteristics of the cements play an important role in developing good concrete strength data so the ready-mix plant can distinguish and relate control strength test data with actual strength in place.

Accelerated strength testing, which is now receiving prominence, cannot be expected to correlate directly with any of the foregoing but it does promise to become useful as a control test because of the advantage of early results. It can be said that accelerated methods for strength testing are now established and quite reliable.

Slump

Slump, or workability, of concrete is normally a field requirement. The portland cement plays a major role in this by its properties of rate of stiffening, initial and final set times, and false-setting tendencies. Admixtures such as set-retarders, set-accelerators, and workability agents are used in controlling workability of concrete but continued uniformity of both cement and admixture is necessary to maintain a constant water requirement - a major determinant of strength; variability in one can nullify constancy in the other.

To retain slump on long hauls and long waits the ready-mix supplier is especially vulnerable to the bad practice of adding water at the site. In addition to false set or rapid stiffening of cement, excessively high temperatures or degradation of aggregates may also lead the ready-mix supplier to add water.

Reduction in Cement Content of Concrete

Water reducers are used extensively in ready-mix production, primarily to lower cost by reducing cement requirements. This can be justified in some cases but should be avoided, or limited, in the case of the leaner mixes or the low strength concretes. Apart from the matter of strength enough cement should be present to almost fill voids after hydration. To a degree this applies to the use of fly ash and other pozzolans as well. Durability of concrete is of prime concern and is linked closely with a limited voids content of the concrete.

Reduction in Number of Mix Designs

For reasons of economy and quality the ready-mix producer should keep the number of his mix designs to a minimum. In one extreme case several years ago a producer had over 100 active mix designs. One reason for escalation of the number of mix designs is the frequent practice of the user of concrete to specify content of cement. Today the ready-mix producer should take a stronger position in deciding what type of mix is best for a given job. To do this he must extend his knowledge of the technology of concrete to field conditions and field performance. He will then be able to develop a reasonably limited number of reliable mix designs to cover the different situations likely to arise in his area.

The ready-mix producer will find it necessary in this connection to study and develop alternatives to some of the special requirements of some jobs. For example, instead of using a low-heat cement, it may be found equally beneficial to provide precooled concrete. For some cases, the accelerator, calcium chloride, will perform adequately instead of using high early strength cement.

Testing and Quality Control

The various properties of portland cement that can be tested, in the dry state, as paste, and in hardened mortars and concretes, have already been considered. In all cases test methods have been established. In most cases test data are available, or can be readily made available, through the cement supplier. This applies to properties covered and not covered by CSA specifications.

In addition, it is essential that, to some extent at least, cylinder and other control tests be extended in the ready-mix plant to follow the performance of cement on a continuing basis. It is also common practice to retain a commercial testing laboratory to make certain control tests on a routine basis.

An essential part of a quality control system is the testing of the concrete delivered at the job site and the recording of its performance in important cases, e.g., finishing operations. In this way the influence of time of haul, degree of mixing and agitation, and degradation of aggregates, can be determined in relation to the cement component. An ideal situation would involve a mobile testing unit commuting between jobs.

SUMMARY

The cement component used in concrete is complex and, to a degree, variable in performance. To reduce this variable to a minimum and obtain a reasonably uniform product, the ready-mix producer can extend his specification requirements to include upper and lower limits to certain critical properties. To obtain control over properties important to him that are not provided with limits in simple quality specifications, he can set his own requirements. Advice on significance of test methods and properties, and on the choice of practicable limits, can be obtained from independent research agencies specializing in concrete. Most coment test data is already available or can be made available by the cement supplier on a routine basis. Test methods have been established.

To reduce further the effects of variation due to the cement, the ready-mix plant should provide its own test results, possibly supplemented by outside, independent testing. These can be based on routine concrete cylinder tests but other tests could be set up to check such properties of the concrete as bleeding.

Finally, the ready-mix operator should reduce the demands on him from the user be he the architect, consulting engineer, contractor, or even the foreman. By extending his knowledge of field conditions and concrete performance he should be able to simplify his operations by reducing his number of mix designs; he could thus provide a more uniform product on a given job.

The day is rapidly approaching when the ready-mix concrete producer must become a real expert in the general field of concrete technology. One way of becoming more knowlegeable on this subject is the active participation in specification committees on cement, aggregates, admixtures, and concrete. CSA committees concerned with these areas are empowered to develop recommended practices.

TABLE I

CSA - A5 CHEMICAL REQUIREMENTS FOR PORTLAND CEMENT

Property	Normal P.C.	High Early P.C.	Sulphate Resist. P.C.
	Maximum Per cent		
Loss on Ignition	3.0	3.0	3.0
Insoluble Residue	0.7	0.7	0.7
Sulphur Trioxide			
$C_3A > 8.0\%$	3.0	3.5	—
$C_3A \leqslant 8.0\%$	2.5	3.0	2.5
Magnesium Oxide	5.0	5.0	4.0
Tricalcium Aluminate	—	—	4.0

TABLE II

PHYSICAL REQUIREMENTS

Property	Normal Portland Cement	High Early Strength Portland Cement	Sulphate-Resisting Portland Cement
Fineness (200 Mesh Test)			
Maximum Retained, Per cent	18	—	18
Soundness (Autoclave Test)			
Maximum Expansion, Per cent	1.0	1.0	1.0
Sulphate Resistance (Integral Test)			
Maximum Expansion Per cent	—	—	0.035
Time of Setting — Vicat Method			
Initial Set, minutes (minimum time)	45	45	45
Final Set, hours (maximum time)	8	8	8
Compressive Strength (2-In. Cube Test)			
Minimum, psi			
Age at test — days			
1	—	1700	—
3	1200	3000	750
7	2100	—	1500
28	3500	—	3000