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A REVIEW OF THE PROPERTIES AND STRENGTH DEVELOPMENT OF NON-FERROUS SLAGS AND PORTLAND CEMENT BINDERS

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Canada

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E. Douglas and V.M. Malhotra***

SYNOPSIS

This study presents a state-of-the-art review of the advances in research and in practical applications of copper, nickel, and lead slags as partial portland-cement replacement in cemented mine backfill and in concrete. Recent research shows that glass content and pozzolanic properties of non-ferrous slags are not directly related and that grindability of the slags seems to be a function of the degree of vitrification. Compressive strength tests on mortars show that air-cooled, non-ferrous slags can outperform granulated slags, depending on the fineness. During hydration, the slags seem to accelerate the rate of C_3S hydration but do not seem to react immediately with the $Ca(OH)_2$ liberated. Non-ferrous slags appear to have considerable potential for partial portland-cement replacement in cemented mine backfill and, to a degree, in concrete. Research is needed to define the areas of additional applications, as well as limitations, to the use of non-ferrous slags.

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EXAMEN DES PROPRIÉTÉS ET DE LA RÉSISTANCE DES LIANTS COMPOSÉS DE LAITIER NON FERREUX ET DE CIMENT PORTLAND

E. Douglas et V.M. Malhotra***

RÉSUMÉ

Le présent document contient une analyse récente des progrès réalisés au niveau de la recherche et des applications pratiques du laitier de cuivre, de nickel et de plomb comme matériau de remplacement partiel du ciment Portland dans le remblai aggloméré des mines et dans le béton. Les résultats de recherches récentes indiquent que la teneur en verre et les propriétés pouzzolaniques du laitier non ferreux ne sont pas directement reliées et que la friabilité du laitier semble varier selon le degré de vitrification. Des essais de résistance à la compression effectués sur des mortiers démontrent que le laitier non ferreux refroidi à l'air peut donner un meilleur rendement que le laitier granulé et ce, suivant sa finesse granulométrique. Pendant l'hydratation, le laitier semble accélérer le taux d'hydratation du C_3S, mais ne semble pas réagir immédiatement avec le $Ca(OH)_2$ libéré. Le laitier non ferreux semble offrir de grandes possibilités en tant que substitut partiel du ciment Portland dans le remblai aggloméré des mines et, jusqu'à un certain point dans le béton. Il est nécessaire de poursuivre les recherches afin de déterminer les secteurs qui se prêtent à de nouvelles applications de même que les limites qui restreignent l'utilisation du laitier non ferreux.

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INTRODUCTION

Wastes generated by the mining, mineral, and metallurgical processes contain metallic and mineral materials that are recoverable. Growing interest in such wastes has been caused by increasing exploration, mineral beneficiation, increasing cost of waste disposal, exhaustion of favourably located high-grade mineral deposits, and legislation restricting mining operations near populated areas. These facts have prompted studies on the feasibility of recovering metals and minerals from more accessible mineral ore and from sources such as mineral wastes.

Basically, most of those mineral wastes not dumped in waste dumps are used as fillers, soil additives, aggregates, and railroad ballast. More important, however, are both the utilization of mineral wastes (such as slags) as portland-cement replacement in cemented mine backfill and in concrete, and the realization that mineral wastes are byproducts in which significant energy had been invested and lost through disposal (Fig. 1). Vitrification and grinding of ferrous wastes, such as blast-furnace slag, produces a material that can be added at the mixer as portland-cement replacement in concrete manufacturing (1).

In Canada, vitreous (pelletized) iron blast-furnace slag is produced at a rate of 2.2×10^5 metric tons per annum in Hamilton, Ontario. In Sault Ste. Marie, Ontario, a plant is under construction to produce 200 000 metric tons per annum of granulated blast furnace slag at the Algoma steel plant. Approximately 45% of the blast-furnace slag produced in Hamilton is used in concrete manufacture (2).

Although the technology of utilization of granulated ferrous slags as cementing materials has been developed in Europe and North America, the utilization of non-ferrous slags as cementitious materials is not well established in concrete manufacture (3,4). The use of copper slags in mine backfill is current practice in Australia, where about 50% of the portland cement used in mine backfill at Mount Isa, Queensland, has been replaced by granulated ground copper slag, resulting in lower production costs (3).

In Europe, Australia, and Canada some copper, nickel, and lead slags have been evaluated for performance as cementitious components in mine backfill (4,5,6) and in concrete (7,8). Approximately 4.1×10^6 metric tons per annum of non-ferrous slags are produced in Canada, of which little is used as railroad ballast and engineering fill. The current accumulation amounts to about 17×10^6 metric tons.

Ferrous slags are siliceous or alumino-siliceous byproducts of metallurgical processes. These slags possess little or no cementitious value, but in finely divided form and in the presence of moisture they react with alkali and alkaline earth hydroxides* at ordinary temperatures to form compounds possessing cementitious properties (9). Under the same conditions, cementitious properties can be conferred on non-ferrous slags.

Copper and nickel slags are extracted from sulphide concentrates by pyrometallurgical treatment. The process includes three different operations:

— ***roasting***, in which sulphur is eliminated as SO_2 and iron is oxidized;

— ***smelting***, in which the product of roasting is melted with a siliceous flux, forming a liquid iron silicate slag which floats on the heavier molten sulphide matte;

— ***converting***, in which sulphur is driven off the sulphide melt and the remaining iron is oxidized and fluxed for removal as a silicate slag.

Converter slag is usually returned to the smelter since it is rich in metal content, whereas smelter slag is either discarded without further treatment or granulated with excess water. These slags possess a high degree of hardness and porosity and vary in unit weight and chemical composition because of differences in ore type, furnace or smelter operations, and slag cooling procedures.

This study is a state-of-the-art review of the advances in research and in practical applications of copper, nickel, and lead slags. It is expected that a critical review could direct future research toward the use of significant amounts of a valuable resource.

*This refers to NaOH, KOH, and $Ca(OH)_2$.

NATURE OF NON-FERROUS SLAGS

CHEMICAL COMPOSITION

Despite the differences in process types, the slags are of similar chemical composition and all may be considered to be represented in the CaO-SiO_2-Fe_2O_3 system (Fig. 2).

The bulk composition of some Canadian slags is shown in Table 1 (10). A recent study on the characterization of Canadian non-ferrous slags (Table 2) shows that determination of the bulk chemical composition with an electron microprobe, operated at 15 kV accelerating voltage, differs somewhat from the chemical composition determined by analytical methods (11).

GLASS CONTENT

Data have been published by McGuire (12) on the glass content of non-ferrous slags from Canadian sources such as a nickel-copper electric furnace slag granulated by quick quenching. The glass content was measured by X-ray diffraction and reported to be 95% (13). The slag was too opaque for a reliable glass count by the optical method using polarizing light, similar to that adopted for quality control of iron blast-furnace slag (14).

Measurements of glass content by a method that uses scanning electron microscopy (SEM) and image analysis were reported by Douglas et al. (15) in a study on the hydration and the pozzolanic activity of ambient-cooled, and of quenched, copper reverberatory furnace* slags from Northern Quebec (Table 3). The glass content in the *air-cooled* slag was 45%; in the *quenched* slag, it was 75 to 95%. The composition of the glass was also reported (Table 4), showing the difference between the glass in the air-cooled slag and the quenched slag due to segregation of Al_2O_3, SiO_2, K_2O, and CaO during quenching. The results did not agree with those published by Roper et al. (16) who estimated a ratio of amorphous-to-crystalline phase of approximately 1:1 in a quenched copper reverberatory slag.

PROPERTIES OF NON-FERROUS SLAGS

GRINDABILITY

Information on grindability, energy requirements for grinding, and particle size distribution of ground non-ferrous slags is limited. Laneuville (5) reported the estimated power required to grind air-cooled and granulated nickel slags to various finenesses based on the duration of the grinds (Table 5).

The particle size distribution of a nickel-copper electric furnace slag, ground to a specific surface of 3 000 cm^2/g, was reported by McGuire (12) and is shown in Table 6. Size distribution of ground nickel slags from Copper Cliff, Ontario, tested for pozzolanic activity is shown in Table 7 (17).

More recently, a study by Douglas et al. (10) on the grindability of a number of Canadian copper, nickel and lead slags compared it with that of a portland-cement clinker containing 3% gypsum. For calibration of grinding time and energy consumption, the grinding energy requirement for portland-cement clinker with 3% gypsum was taken as 31 kWh/t to develop a specific surface of 3 000 cm^2/g and 43 kWh/t to develop a specific surface of 4 000 cm^2/g. From this information about grinding energy consumption, a scale-up from laboratory mill to typical production mill was estimated as 1 min = 0.4 kWh/t, which is a value dependent on the specific laboratory.

Grinding data are given in Table 8, in terms of initial gradation, actual fineness (Blaine method), time to achieve specific fineness, and energy consumption for producing materials of 2 000, 3 000, 4 000 and 5 000 cm^2/g as well as specific gravity and per cent passing 45 μm (10).

Figure 3 shows the estimated energy consumption required for production grinding of the slag samples compared to that required to grind blast-furnace slag and portland-cement clinker with addition of gypsum to a specific surface of 4 000 cm^2/g. Grinding energy in increasing order, a comparison to an initial minus 75 μm size, major oxide composition, and estimated degree of vitrification are given in Table 9 (10).

From the data collected, it would appear that the grindability of non-ferrous slags is a function of the degree of vitrification. Slags with higher glass contents generally require more grinding time.

*A reverberatory furnace is a furnace in which smelting of the concentrate takes place.

POZZOLANIC ACTIVITY

Pozzolanic materials contain fine, active silica which reacts with lime and water to form stable cementitious, hydrated calcium silicates. For hydraulic cement mine backfill, fly ash, ground quenched copper reverberatory furnace slag, and ground blast-furnace slag are materials with proven pozzolanic activity (16). According to Thomas (18), three aspects have to be considered in the use of pozzolanic materials for hydraulic cemented mine backfill:

- reaction causing removal of lime, a material with potentially adverse effects;
- production of a stronger cement due to removal of lime, allowing strength development at a lower portland cement content;
- formation of additional cementing materials from the pozzolanic reaction, resulting in equivalent strength at lower portland cement content.

Experimental evidence of this approach was found by Thomas (3) in the results of a study on the pozzolanic properties of a granulated copper reverberatory furnace slag which showed no obvious alteration after many years in a surface dump. The particle size analysis revealed essentially one component, approximately 2.54 mm in diameter. Test specimens were prepared from pulped mixtures of fill, portland cement, and the slag ground to a specific surface of 3 000 cm^2/g. Strength increases with increasing slag additions at fixed cement content are shown in Figure 4. These results, concerning cost reductions in cemented fill production with no strength loss, were considered significant.

The same slag was tested at a later date in cemented mine fill at high slag/cement ratio (6). The fill contained 80 to 99 wt % of Isa Mine copper sulphide tailings, 1 to 5 wt % portland cement and 0 to 16 wt % slag (Fig. 5). Thomas (6) concluded that slag additions, indicated as non-beneficial at 1 wt % portland cement, were consistently beneficial at 3 and more wt % portland cement, and transitional in benefit at 2 wt % portland cement.

Pozzolanic activity tests on a granulated copper slag were carried out by various methods in Spain (4). The results of tests performed in accordance with ASTM C 618-73 method showed strength above 75 wt % of the control specimens.

Laneuville (5) determined the pozzolanic activity of air-cooled and of granulated nickel slags by ASTM C 595 method and reported that compressive strengths higher than the minimum 800 psi set out in the specifications were obtained with these slags ground to a specific surface in the range 3 800 to 4 000 cm^2/g.

In Canada, strength gains with increasing contents of a granulated nickel-copper electric furnace slag were measured by McGuire (12) in mixes containing 6 wt % of portland cement and a tailing fill of 2.96 relative density (Fig. 6). The strength gains were attributed to chemical bonding, derived from the hydration of a pozzolanic slag.

More recently, slag activity and pozzolanic indexes were determined in accordance with ASTM C 109* for the preparation of the test specimens, and with ASTM C 595** and C 989*** (10) for curing and testing.

Tests were conducted at age 7 and 28 days according to a modified ASTM C 989 standard, where 50% of portland cement measured by absolute volume, was replaced by the ground non-ferrous slag, thus taking into account the different specific gravity of the slags (Table 10).

Significant strength development due to pozzolanic activity is shown in Figure 7. The strength development for 28 days curing at 38°C, for mortars with 20, 35, 50 and 70% ground non-ferrous slag replacing portland cement, is shown in Figures 8 to 10. Activators, such as NaOH, and the replacement of portland cement by cement kiln dust did not improve compressive strengths (10).

Effect of glass content on pozzolanic activity

The effect of glass content on the pozzolanic properties of Canadian non-ferrous slags can be assessed by comparing strength development data of air-cooled and of water-quenched slags (5,19).

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*ASTM C 109: Compressive strength of hydraulic cement mortars using 50 mm cube specimens.

**ASTM C 595: determination of pozzolanic activity and of slag activity index with portland cement on specimens cured in a moist room at 23°C for 24 h, and at 38°C in sealed containers after removing from the mold, for the balance of the time, to 28 days.

***ASTM C 989: determination of slag activity with portland cement. The following specifications were introduced: (a) replacement of 50% of the portland cement by the slag was done by absolute volume and not by weight, and (b) the specimens were cured at 23°C in the moist room to the specified age.

Pozzolanic activity tests of binders for mine backfill were performed in Canada (20) with air-cooled and with quenched nickel and copper-nickel slags at different cement replacement levels. The chemical composition of the slags tested and the mixture proportions of the cemented backfill from which the test specimens were cast are listed in Tables 11 and 12.

Glass content of the air-cooled nickel reverberatory slag was estimated at less than 20%. The change in compressive strength was calculated on the basis of a standard incorporating 4.8 wt % of portland cement (Fig. 11). Maximum changes in strengths were observed after 14 days of curing for a sample incorporating 60% of air-cooled nickel slag. For unknown reasons, better performance occurred in long-term curing of test specimens of a mix incorporating an air-cooled, rather than water-quenched, copper-nickel slag. The mix contained 4.8% cement, 1.2% slag, and 96% tailings.

Results from recent studies on pozzolanic activity of Canadian air-cooled and of quenched non-ferrous slags (10,15) led to the conclusion that, (contrary to results of studies on blast-furnace slag), for non-ferrous slags the glass content and pozzolanic activity are not directly related. Test specimens of mortars with 35 and 70% cement replacement were prepared according to ASTM C 595, but cured at room temperature (15). Results of pozzolanic activity studies (Table 13) indicate that air-cooled copper slags could, depending on their fineness, outperform–or at least equal–the performance of quenched copper slags. Similar results were reported on pozzolanic tests carried out on granulated nickel, copper, and lead slags, according to ASTM C 595 (21). Pozzolanic and slag activity indexes are shown in Table 14.

Effect of fineness on pozzolanic activity

Laneuville (5) evaluated the relative strength of mortars prepared in accordance with ASTM C 109, in which 30% of the cement was replaced by air-cooled nickel slag, ground to different finenesses. The strength of the test specimens was compared to that of a portland-cement mortar at various curing ages (Table 15). *The experimental results indicate that compressive strengths are directly related to fineness.* Laneuville (5) also studied the effect of fineness on the hydraulic index at different curing ages (Fig. 12).

The data indicate that granulated slags ground to 3 000 cm^2/g performed better than air-cooled slags ground to 4 000 cm^2/g. Nevertheless, air-cooled slags ground to 7 000 cm^2/g performed better than the rest of the slags (Table 15). A more recent study indicates that the effect of fineness on the pozzolanic activity of Canadian copper, nickel, and lead slags, for both air-cooled and quenched samples, is directly related to pozzolanic activity as shown in Tables 13 and 14 (21).

HYDRATION OF NON-FERROUS SLAGS

Chemically, inorganic cementing materials derive from the multi-component system:

$$CaO\text{-}MgO\text{-}SiO_2\text{-}Al_2O_3\text{-}Fe_2O_3\text{-}SO_3$$

Portland cement, natural pozzolans, most fly ashes and many blast-furnace slags may generally be considered on a simplified ternary system $CaO\text{-}SiO_2\text{-}Al_2O_3$ with minor or insignificant amounts of MgO, SO_3 and Fe_2O_3 (Fig. 2a). Steel slags and non-ferrous slags are better represented by the system, $CaO\text{-}SiO_2\text{-}Fe_2O_3$, where CaO represents the sum of CaO, MgO and Al_2O_3 (Fig. 2b).

Approximately 70 to 75 wt % of portland-cement clinker is tricalcium silicate (C_3S) and β-dicalcium silicate (β-C_2S) with small amounts of Al_2O_3 and MgO dissolved in them (22). In addition, small amounts of calcium sulphate, usually in the form of gypsum, are added to portland-cement clinker during the grinding operation for the purpose of controlling the initial hydration reactions.

Natural pozzolans of volcanic origin are composed of a vitreous phase of microporous texture with small amounts of a crystalline phase (23). The silica and alumina, that constitute the vitreous pyroclastic component, combined with lime in aqueous media yield insoluble cementitious products. The reactivity of pozzolans is determined not only by the structure, morphology, and chemical composition of the vitreous phase, but also by the fineness of the material (24), type and quantity of lime in the system (25,26) and water content (27).

Different hydration products have been identified on various pozzolan-$Ca(OH)_2$ systems. In some cases, C-S-H together with C_2ASH_8, or C-S-H, C_2ASH_8, hydrogarnet and ($C_3A.CaCO_3H_{12}$-C_4AH_{13}) were found, depending on the composition of the pozzolan. The CaO/SiO_2 ratio in the C-S-H is believed to be closely related to the concentration of Ca^{2+} in the solution (28).

The composition of slags depends on their origin. Copper slags analyzed by scanning electron microscopy (SEM) (15) show that slags appear as intergrowths of fayalite, spinel, glass and copper sulphides. Results of optical and SEM studies carried out in Spain (4) on granulated copper slags showed that the crystalline phase was composed mainly by needle-like fayalite (Fe_2SiO_4) and globular iron oxides.

Not much is known about the composition of other slags. It might be expected that materials as diverse as portland cement, pozzolans, and ferrous and non-ferrous slags would react with water to form markedly different compounds. In practice, there is a remarkable similarity in the reaction products from these materials. The common factor in all of these systems is the ultimate formation of C-S-H and the correspondence between its formation and the development of structural bonds in the hydrating mass.

Kam (29) studied the hydration of copper reverberatory furnace slag in the presence of $Ca(OH)_2$, $CaCO_3$, and portland cement. The experimental analysis of the hydration products comprised measurements of early heat of hydration, determination of non-evaporable water in the reaction products, quantitative X-ray diffraction analysis, and scanning electron microscopy.

Kam reported that the rate of heat evolution decreased as the proportion of slag increased. Also, the amount of non-evaporable water increased as the amount of slag in the paste increased. Kam's studies also showed an unidentified diffraction peak at 7.34 Å in the X-ray diffractograms for all the hydrated slag-$Ca(OH)_2$ pastes. The X-ray diffraction study showed also that the fayalite crystals do not take part in the hydration reactions. Such reactions are limited to the glass phase.

Roper et al. (16) reported that copper reverberatory furnace slag need not be completely glassy for significant hydration to occur. Recent investigation by Douglas et al. (15) on an air-cooled copper slag with 41% glass and on a quenched copper slag with 95% glass, showed that the presence of the slag delays the transfer of Ca^{2+} from the portland-cement constituents to the solution at the early stage of hydration.

In the later stage, between 24 and 72 hours of hydration, the measured Ca^{2+} concentration in the solutions in contact with the binders and the percentage of $Ca(OH)_2$ in the solid phase at the same age suggest that more C_3S from the portland cement had reacted in the slag blend than in the portland-cement paste. Although the study showed that air-cooled slags may outperform quenched slags, depending on the fineness, further research in this area is needed.

STRENGTH DEVELOPMENT OF MINE BACKFILL MATERIAL INCORPORATING NON-FERROUS SLAGS

Most of the studies intended to encourage the use of copper, nickel, and lead slags have been directed toward exploring the feasibility of their use as cement replacement in cemented mine backfill. Strength development of copper reverberatory furnace slag, de-zinced lead smelter slag, and copper converter slag in cemented fill were first studied by Thomas (3,6) in Australia and his data are shown in Figures 4 and 5.

Kam in a recent study (29) showed that significant strength could be developed with slag-$Ca(OH)_2$ mixes, where higher $Ca(OH)_2$ content would lead to higher strength (Table 16). Strength development, equivalent to that obtained with portland cement-slag mixes, can be achieved with cemented fill using copper reverberatory furnace slag and lime mixtures (29). Variations in the strength of fill at early ages are mostly affected by density and water content (Table 17), both of which are related to consolidation conditions.

At later ages, variations in strength are affected by the amounts of hydrated cementitious materials in the mix. Improvement in compaction methods of backfill in stopes should be an important goal, if early strength development is required. According to Kam (29), increased compaction could be achieved by rapid drainage of the wet fill as it is being placed, and vibration methods should also be explored. Changes in the grain size distribution of the fill materials, such as rejected slimes, may improve the particle size distribution and therefore the compaction of the fill material.

A recent study by Emery (21) reports tests at 7, 28, and 90 days on a granulated copper slag from Ontario and a remelted and quenched copper slag from Quebec in mixes with mine tailings (Tables 18 and 19). Measurements were made on 50-mm uncompacted cubes containing 70% mine tailing. The cubes were demolded when sufficient strength was obtained; they were stored in the moist room at 23°C; after 28 days the specimens were tested for compressive strength. It was found that little improvement in strength developed in the cementitious systems with 12 wt % slag and 4% portland cement, compared with the blend of 4 wt % slag and 4% portland cement.

A decrease in compressive strength between 28 and 90 days was also reported. It would appear that most of the cementitious properties were due to the portland cement and that lower compressive strength at 90 days may be related to the components in the tailings causing chemical reactions during curing. It is doubtful that this will be a factor in actual applications.

STRENGTH DEVELOPMENT OF MORTARS AND CONCRETE INCORPORATING NON-FERROUS SLAGS

Tests for strength development of mortars incorporating non-ferrous slag binders have been conducted by Laneuville (5) and by Baragano (4) using nickel and copper slags. Reports of research on the use of lead slags as partial portland-cement replacement in steam-cured blocks have been published recently (7). The specimens were made with ground lead slags and calcium-bearing materials such as lime, gypsum, and portland cement. Mixtures had been prepared consisting of 3 parts of sand and 1 part of a binder formed by different combinations of ASTM Type III portland cement and a lead slag ground to 2 500 cm^2/g. The results showed that up to 25 wt % ground slag can replace cement before significant strength loss occurs (Fig. 13).

Tests on strength development of mortars, some incorporating air-cooled, granulated and quenched lead, nickel and copper slags from Canadian sources, have been reported and data are shown in Table 18 (21). Portland cement in the mortar was replaced by the slag. The mortars were cured at 38°C for 28 days. Higher strengths were observed in air-cooled than in quenched nickel slags. Strengths of granulated copper slag from the province of Ontario were slightly improved by adding 20% CaO to the melted slag and quenching in excess water.

Investigations by Emery (21) show that air-cooled copper reverberatory furnace slag from the province of Quebec exhibited higher strengths than the quenched slag from the same source at the same fineness in some of the specimens; some of his data are shown in Table 20. Another series of tests was performed with mortars in which 50% of the portland cement had been replaced by the slag (21). The mortars were cured at room temperature (23°C) and tested at 1, 7, 28 and 90 days (Table 21). The results show that several slags appear to have portland-cement replacement potential at the 4 000 Blaine level.

Douglas and Mainwaring (15) have reported strength development of mortars of portland cement-copper slags binders with 35 and 70% cement replacement. The mortars had been placed in close-fitting containers stored at 23 ± 1.7°C and tested at 1, 7, 28, and 90 days (Fig. 14a,b).

The compressive strength of mortar incorporating 35% of air-cooled slag ground to 4 000 cm^2/g (Blaine method) was higher than that of a mortar incorporating 35% of the quenched slag with the same fineness. At 90 days the strength of the former attained that of the portland-cement mortar used as a control. In mortars with 70% replacement, the mortar incorporating the quenched slags developed higher strength than that incorporating the air-cooled slag.

Other recent studies on Canadian non-ferrous slags showed that some slags ground to 4 000 cm^2/g outperform the corresponding 3 000 cm^2/g materials. However, many of the 3 000 cm^2/g materials are sufficiently reactive to save the extra grinding costs (11).

Details of a recent study on concrete mixes, incorporating Canadian ground non-ferrous slags have been reported (21), and their compressive strength development are shown in Tables 22, 23, and 24. Table 24 shows the effect of a water-reducing admixture on compressive strength development at different ages. Tables 23 and 24 allow comparison of the concrete mixes incorporating ground non-ferrous slags in terms of both compressive strength development at 7, 28, and 90 days, and compressive strength ratio to the control at the same ages.

Figure 15 shows compressive strength development, and Figure 16 the compressive strength ratio. Evidently the compressive strengths of concrete mixes incorporating lead slag at 90 days is equivalent to the compressive strength of the control at 28 days.

EFFECT OF GLASS CONTENT ON STRENGTH DEVELOPMENT

Limited information is available on the relationship between glass content and strength development with time for portland-cement concrete incorporating non-ferrous slag. Results on strength development of non-ferrous slag binders, both air-cooled and quenched, were reported in a Canadian patent (5). Mortars made with 70:30 cement-to-slag ratio were tested for compressive strength (ASTM C 109). Nickel slags were used; air-cooled slags were ground to a specific surface of 4 000 cm^2/g, the granulated slags to 3 800 cm^2/g. Results to 90 days of curing indicated that water quenching improved the long-term strength of glassy nickel slag binders.

Douglas et al. (30) have reported tests on strength development of mortars (ASTM C 109) incorporating air-cooled, granulated and quenched lead, nickel and copper slags from Canadian sources. With each test, a different amount of portland cement in the mortars was replaced by the slags. The mortars were cured at 38°C for 28 days. Higher strengths were observed in air-cooled than in quenched copper slags (Fig. 14). Strengths of granulated copper slag from the province of Ontario were slightly improved by adding 20% CaO to the melted slag and quenching in excess water. Air-cooled copper reverberatory furnace slag from the province of Quebec exhibited higher strengths than the more glassy quenched slag from the same source in some of the specimens.

Another series of tests was performed with mortars (ASTM C 109) in which 50% of the portland cement was replaced by the slag (31). The mortars were cured at room temperature (23°C) and tested at 1, 7, 28, and 90 days (Table 21). The results show that some slags ground to 4 000 cm^2/g and cured at 90 days outperformed the control specimens.

Strength development in mortars of portland cement-copper slag binders with 35 and with 70% cement replacement was recently reported by Douglas and Mainwaring (15). The mortar cubes (ASTM C 595) were tested at 1, 7, 28, and 90 days (Fig. 17). The compressive strength of mortar incorporating 35% of air-cooled slag ground to 4 000 cm^2/g (Blaine method) was higher than that of a mortar incorporating 35% of the more glassy quenched slag. At 90 days the strength of the former attained that of the portland-cement mortar used as control.

EFFECT OF FINENESS ON STRENGTH DEVELOPMENT

Improved strengths of finer granulated blast-furnace slags reported in the literature (32) led some investigators to study the effect of fineness in strength development of nickel slag binders (5). Compressive strength data were reported on mortars (ASTM C 109) containing 70% portland cement and 30% air-cooled nickel slag. The mortars were cured in water at 23°C. An increase of approximately 15% in compressive strength after 90 days was observed for specimens made with slags ground to 4 000 cm^2/g, compared to those slags ground to 3 000 cm^2/g.

Data on mortars made with an air-cooled nickel slag of similar chemical composition but with a MgO content 2% higher than in the first sample were also reported (5). Strength development of the two air-cooled slags was approximately the same when ground to a specific surface of 4 000 cm^2/g. Increasing the specific surface to 7 700 cm^2/g resulted in approximately 15% increase of compressive strength at 90 days. Strength development of mortars incorporating air-cooled nickel slag ground at different fineness and cured at 23°C are shown in Figure 18 (5). Compressive strengths at 28 days of mortars incorporating lead, nickel or copper slags ground to 2 000, 3 000, 4 000 and 5 000 cm^2/g were reported in Canada (Table 21) (29).

EFFECT OF SLAG CONTENT ON STRENGTH DEVELOPMENT

Apparent discrepancies have been reported on the effect of slag content on the strength development of nickel slag binders. Thomas (33) found increasing strength in mixes of tailings with a fixed amount of portland cement and copper slag content about double that of cement.

Laneuville (34) reported negligible contribution of a granulated nickel slag to early age strength and a progressively greater contribution after 90 days of wet curing at 21°C for binders containing less than 45% slag (Fig. 19).

The discrepancy between the two sets of results, those of Thomas and those of Laneuville, was explained by Laneuville in terms of the decreasing ratio of water to cementitious materials when larger amounts of slag are added to a constant amount of portland cement. Measurements of the combined water in mortars of slag binders showed a direct relationship between compressive strength and combined water (Fig. 20).

EFFECT OF ACTIVATORS ON STRENGTH DEVELOPMENT

Low compressive strength values at early ages obtained in mortars with 65:35 portland cement to copper slag ratio led researchers to the study of the effect of alkaline activators on early strength (4). Atwell (1) reported that when 5 to 10% of precipitator dust with an alkali oxide content of approximately 5% was added to mortars made with portland cement-copper slag blends, an increase of up to 25% in compressive strength at 7 days was observed.

The effect of calcium carbonate and calcium chloride on air-cooled and on granulated nickel slag was investigated by Laneuville (5) in mortars with 30% portland-cement replacement with slag. He concluded that the compressive strength of nickel slag mortars does not improve by increasing its basicity.

Activation with calcium chloride was found effective for improving the performance of air-cooled slags after 7 days curing (Fig. 21). The results showed improvement of strength at all ages in granulated slags with addition of 2% calcium chloride.

Laneuville (5) tested the effectiveness of precipitator dust used as an activator. The kiln dust contained 16.8% potassium oxide and 9.5% free calcium oxide. He concluded that the incorporation of cement precipitator kiln dust in portland cement-nickel slag binders yielded binders with improved early strength characteristics and properties close to those of portland-cement mortars.

Recent studies, however, indicate that the activation of lead, nickel, and copper slags by addition of Na(OH) to the mixing water, at a concentration of 200 g/L, or by replacing portland cement by cement kiln dust, does not result in satisfactory performance (10).

DURABILITY OF MORTARS INCORPORATING NON-FERROUS SLAGS

The performance of concrete with partial replacement of cement by non-ferrous slags possessing pozzolanic properties is not known. Baragano (4) reported results of tests on mortars on the protective capacity against corrosion for steel reinforcement. Good results were observed for copper slag-cement blends without addition of calcium chloride as an activator.

Baragano (4) has also reported results on tests for resistance to sulphate attack on mortars with copper slag-portland cement blends. Calcium, magnesium and sodium sulphate solutions as well as sea water were used as aggressive agents. The greatest resistance was shown by a slag cement with 35% copper slag, compared with portland-cement mortar or with portland cement blended with 35% natural pozzolan. Similarly, the freezing and thawing tests on mortars indicated better performance with copper slag than with natural pozzolan.

CONCLUDING REMARKS

1. Non-ferrous slags appear to have considerable potential for partial portland-cement replacement in cemented mine backfill and in concrete.

2. Additional research work needs to be done to define areas of applications as well as limitations on the use of non-ferrous slags.

SUGGESTED RESEARCH

A research program directed towards the use of non-ferrous slags in cemented mine backfill and concrete should include:

1. development of standards for quality control;
2. development of tests for detection of potential health hazard due to leaching of deleterious elements;
3. tests for resistance of concrete to external agents.

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TABLES

Table 1 — Chemical analysis of Canadian non-ferrous slags (wt %) (10)

	A Lead (N.B) granulated	B Nickel (Ont.) air-cooled	C Nickel (Ont.) quenched	D Copper (Ont.) granulated	E Copper (Ont.) quenched	F Copper (Que.) air-cooled	G Copper (Que.) air-cooled	H Copper (Que.) quenched	I Copper (Que.) granulated
SiO_2	19.1	35.66	37.25	26.54	22.10	36.26	34.51	36.78	34.41
Al_2O_3	1.66	5.59	6.17	3.74	2.94	2.16	6.55	7.16	6.82
Fe_2O_3*	45.35	52.99	53.07	60.07	44.36	49.00	49.50	50.00	49.64
CaO	16.60	2.74	2.97	2.09	20.32	7.30	2.20	1.93	1.66
MgO	0.68	2.53	2.43	1.63	1.52	1.91	1.48	1.49	1.91
Na_2O	0.26	0.87	0.86	0.39	0.23	0.28	1.02	1.06	1.34
K_2O	0.25	0.65	0.62	0.33	0.98	1.26	1.01	0.96	0.66
TiO_2	0.14	0.32	0.33	0.14	0.12	0.13	0.35	0.39	0.28
MnO	0.09	0.07	0.07	0.10	0.08	0.08	0.10	0.09	0.08
Cu	—	—	—	1.10	—	0.48	0.43	0.41	0.48
Ni	—	0.23	0.25	—	—	—	—	—	—
Pb	4.84	—	—	—	—	—	—	—	—
LOI**	−5.75	−5.32	−6.00	−5.84	−4.39	−3.91	−5.24	−6.13	−4.73
S	1.30	1.46	1.39	1.28	0.45	1.01	1.20	1.13	1.00

*Total iron expressed as Fe_2O_3.

**LOI at 700°C. Negative values indicate a gain after ignition caused by oxidation of FeO and S^2.

Table 2 — Bulk composition of Canadian non-ferrous slags (wt %)

Element	J	I	C,D	G,H
FeO	55.1	44.6	50.3	40.9
CaO	2.1	16.7	3.5	17.6
ZnO	6.2	3.9	—	12.3
MgO	1.8	1.8	2.5	—
Al_2O_3	4.2	4.2	5.9	1.5
K_2O	0.4	0.4	0.7	0.2
CuO	—	—	—	0.1
PbO	—	—	—	3.0
TiO_2	—	—	0.3	—
SiO_2	32.1	30.6	36.6	23.5
S	0.8(s)	0.6(s)	1.5(s)	1.6(s)
Totals	101.9	102.8	101.3	100.7

n.d. = not detected (by E.D.X.A.).

S as sulphur only, not as SO_3 in oxide wt % column.

Table 3 — Copper slag* constituents determined by image analysis (15)

Sample	Fields	R**	Glass	Fayalite	Spinel	Sulphide
G,GB, Air-cooled	30	1.5	41±4	57±6	5±1	0.2
H,HA, Quenched	20	0.3-0.1	75-95	15-5	10-trace	—

*From Quebec.

**Ratio of crystals to glass.

Table 4 — Compositions of glass determined by electron microprobe in copper slags (Quebec)

	A Air-cooled slag	B Quenched slag
MgO	—	1.4 ± 0.03
Al_2O_3	14.5 ± 0.2	10.1 ± 0.2
SiO_2	45.8 ± 0.8	38.6 ± 0.5
K_2O	2.1 ± 0.2	0.6 ± 0.03
CaO	3.6 ± 0.7	1.7 ± 0.04
MnO	0.1 ± 0.02	0.1 ± 0.03
Fe_2O_3*	28.7 ± 3.8	39.4 ± 0.6
ZnO	5.3 ± 0.7	5.0 ± 0.2
PbO	0.8 ± 0.1	0.4 ± 0.1
Total	100.9	101.4

*Total Fe calculated as Fe_2O_3.

Table 5 — Estimated kWh/t required to grind nickel slag (Ontario), calculated from grinding times (15)

	Air-cooled #1	Air-cooled #2	Granulated
Fineness (cm^2/g, Blaine method)			
3000	50	58	88
3500	65	65	107
3800	77	77	117
4000	83	83	128

Table 6 — Particle-size distribution of granulated nickel slag (Ontario) ground to 3000 cm^2/g (12)

Particle size	Weight Percentage	
(micrometres)	Slag	Fill
+ 208	0.5	9.5
+1147	0.5	17.2
+ 104	0.7	16.7
+ 74	2.4	16.3
+ 53	9.7	11.3
+ 38	10.7	15.9
+ 27	29.7	12.2
+ 19	9.7	0.4
+ 13	9.9	0.2
+ 9	6.9	0.1
+ 7	4.42	0.06
+ 5	4.97	0.05
+ 3	4.97	0.05
+ 2	3.38	0.03
− 2	1.36	0.01

Table 7 — Size distribution, surface area, and specific gravity of ground nickel slags (Ontario) tested for pozzolanic activity (17)

(a) Size Distribution	CC Dump**	
Microns	Wt %	Cum Wt
+74	0.09	0.09
45	0.14	0.23
37	0.09	0.32
23	2.57	2.89
17	12.88	15.77
13	14.08	29.85
−13	70.15	100.00
(b) Surface Area	S.A. (cm^2)	
Blaine (cm^2/g)	4437	
B.E.T. (m^2/g) (Gas adsorption)	20.9	
Specific gravity	3.30	

**CC dump slag stands for Copper Cliff dump slag.

Table 8 — Energy consumption for grinding non-ferrous slags (10)

Sample	Average fineness measured cm^2/g				Grinding time min				Energy consumed kWh/t				Specific gravity* cm^2/g	% passing 45 μm			
	a	b	c	d	a	b	c	d	a	b	c	d		a	b	c	d
A	2029	2970	3891	5012	75	180	653	1335	30	72	261	534	4.00	76.52	85.55	87.59	88.52
B	2080	3044	4047	5026	50	75	115	178	20	30	46	71	3.54	70.57	83.68	91.49	94.59
C	2025	3098	3935	5019	60	75	120	210	24	30	48	84	3.45	69.49	86.94	91.32	95.16
D	2012	2976	4014	—	95	195	600	—	38	78	240	—	3.90	69.04	79.48	80.92	—
E	1995	3168	4095	4923	55	140	210	365	22	56	84	146	3.68	59.65	—	91.36	95.31
F	2034	3104	3955	4966	50	120	190	285	20	48	76	114	3.73	56.63	82.80	87.50	92.49
G	1979	3107	3927	4999	50	118	190	325	20	47	76	130	3.53	59.84	77.36	82.61	88.63
H	1985	3150	4138	4936	63	122	240	360	25	49	96	144	3.39	62.34	90.41	92.23	92.61
I	1987	2999	4049	5087	70	103	190	280	28	41	76	112	3.50	68.04	85.42	91.68	93.09
J	2032	2981	4118	4983	55	105	240	360	22	42	96	144	3.40	49.39	89.97	93.88	94.92
K	1975	2975	3968	—	70	240	600	—	28	96	150	—	3.58	63.12	71.77	73.82	—
L	1951	3031	3985	5038	65	140	240	420	26	156	96	168	3.40	66.04	92.42	93.79	94.47

Note: a, b, c, d indicate slags ground to 2000, 3000, 4000, and 5000 cm^2/g, respectively.

*Specific gravity determined in samples ground to 4000 cm^2/g.

Table 9 — Grinding energy requirements and compositional characteristics of non-ferrous slags* (10)

Slag**	kWh/t	−75 μm %	SiO_2 %	Fe_2O_3 %	Vitrification***
B	46	8	35.7	53.0	crystalline
C	48	1	37.2	53.1	glassy/crystalline
F	76	2	36.3	49.0	crystalline
G	76	3	34.5	49.5	crystalline
I	76	1	34.4	49.6	glassy/crystalline
E	84	0.9	22.1	44.4	glassy/crystalline
H	96	0.5	36.8	50.0	very glassy
J	96	4	42.8	45.8	glassy
L (3000 Blaine 96)	150	0.3	27.2	28.5	very glassy
D (3000 Blaine 78)	240	0.2	26.5	60.1	very glassy
A	261	2	19.9	45.4	very glassy

Note: Energy requirement for grinding portland-cement clinker is 44 MJ/t; for blast furnace slag, 48 kWh/t to 4000 Blaine.

*Slag K was not evaluated.

**Slags ground to 4000 Blaine, cm^2/g, unless indicated.

***Qualitatively estimated by X-ray diffraction.

Table 10 — Slag activity index of non-ferrous slags cured in moist room at 23°C for 50% portland-cement replacement by absolute volume (10)

Blaine fineness	Slag A		B		C		D		E		F		G		H		I		J		K	
	7d	28d	7d	28d	7d	28d	7d	28d	7d	28d	7d	28d	7d	28d	7d	28d	7d	28	7d	28d	7d	28d
2000	35	52	28	39	34	48	29	52	29	46	28	33	30	39	30	44	24	38	25	38	38	55
3000	40	64	28	42	35	52	33	70	35	59	35	43	30	49	40	67	27	39	28	39	46	70
4000	45	81	32	48	37	59	34	73	40	67	38	52	35	56	47	83	33	59	39	59	54	91
5000	58	78	36	68	42	71	NG	NG	51	83	41	58	36	66	55	96	37	70	42	70	NG	NG

Notes: 1. Portland cement meets the requirements of ASTM C 989, "Specification for ground blast-furnace slag for use in concrete and mortars", Table 3.
2. Nominal Blaine, cm^2/g, of slags indicated 2000, 3000, 4000 and 5000.
3. NG indicates slag was not ground to this fineness.

Table 11 — Chemical composition of air-cooled and of quenched nickel slags (Ontario) (17)

	Fe	S	SiO_2	CaO	MgO	Al_2O_3	$\%Al_2O_3+\%CaO+\%MgO/\%SiO_2$ hydraulic modulus
Nickel reverberatory, air cooled	36.0	1.5	35.5	2.25	2.50	5.05	0.2761
Nickel reverberatory, water quenched	35.8	1.4	36.8	2.30	2.45	5.55	0.2799
Flash furnace slag, air cooled	35.8	1.5	30.8	7.00	2.45	6.00	0.5016
Flash furnace slag, water quenched	34.4	1.4	31.0	7.05	2.50	6.50	0.5177
Nickel reverb. + 14% limestone, water quenched	32.9	1.4	32.8	9.40	2.45	5.85	0.5396
Ground quartz	0.58	—	87.7	0.27	0.029	1.10	0.0160

Table 12 — Composition of the specimens incorporating air-cooled and quenched nickel slags (Ontario) (17)

Series No.	1	2	3	4	5	6	7
Description							
Wt % slag	0	0	1.2	4.5	4.5	8.7	16.0
Wt % cement	9.1	4.8	4.7	4.6	4.5	4.4	4.0
Wt % tailings	90.9	95.2	94.1	93.1	91.0	86.9	80.0
Total wt % binders	9.1	4.8	5.9	6.9	9.0	13.1	20.0
% cement replacement	0	0	20	33	50	66	80
Tailings/cement/slag	10:1:0	20:1:0	20:1:25	20:1:50	20:1:1	20:1:2	20:1:4

Table 13 — Pozzolanic and slag activity indexes of portland cement-slag (Quebec) mortars cured at room temperature (21)

PI/HI*	Copper air-cooled	Copper quenched
2000	0.71/0.32	0.67/0.31
3000	0.73/0.36	0.87/0.27
4000	0.89/0.49	0.85/0.70
5000	0.91/0.38	1.06/0.52

*PI:pozzolanic index; HI:slag activity index (hydraulic index).

Table 14 — Pozzolanic and hydraulic indexes of Canadian non-ferrous slags (ASTM C 595) (21)

PI/HI	Lead (N.B.) granulated	Nickel (Ont.) air-cooled	Nickel (Ont.) quenched	Copper (Ont.) granulated	Copper (Ont.) quenched	Copper (Que.) air-cooled	Copper (Que.) air-cooled	Copper (Que.) quenched	Copper (Que.) granulated
2000	0.50/0.25	0.64/0.40	0.55/0.26	0.48/0.24	0.57/0.33	0.49/0.24	0.58/0.39	0.51/0.32	0.56/0.32
3000	0.54/0.27	0.73/0.43	0.67/0.41	0.69/0.29	0.72/0.43	0.67/0.35	0.80/0.49	0.73/0.42	0.70/0.40
4000	0.96/0.29	0.83/0.58	0.78/0.44	0.69/0.31	0.76/0.45	0.70/0.47	0.85/0.59	0.80/0.54	0.79/0.50
5000	1.01/0.36	0.98/0.67	0.88/0.57	NG	0.81/0.52	0.83/0.53	1.02/0.71	0.85/0.69	0.83/0.64

Notes: 1. Nominal Blaine fineness of slags indicated — 2000, 3000, 4000, and 5000.
2. NG indicates slag was not ground to this fineness.
3. PI and HI are the pozzolanic (pozzolanic activity index) and hydraulic (slag activity index), indexes with lime and cement, respectively, in accordance with ASTM C 595.

Table 15 — Relative strength of portland cement-nickel slag mortars showing the effect of fineness (5)

Slag fineness (cm^2/g)	Curing age days	Relative strength (%)
3000 (granulated)	3	63
	7	66
	28	81
4000 (air-cooled)	3	60
	7	72
	28	78
7700 (air-cooled)	3	68
	7	75
	28	90

Table 16 — Uniaxial compressive strength of ground copper reverberatory furnace slag and $Ca(OH)_2$ pastes (29) (Water/solids ratio = 0.30)

CRFS*:$CA(OH)_2$	Strength (MPa)	Mean (MPa)	Standard deviation (MPa)
1:1	6.632	5.851	1.842
	3.314		
	5.834		
	7.622		
2:1	4.678	4.686	0.143
	4.882		
	4.540		
	4.642		

*CRFS: copper reverberatory furnace slag.

Table 17 — Effect of density and water content on compressive strength of fill at an early age (24)

Dry density (g/cm^3)	Water content (g)	Strength (MPa)
2.21	29.7	2.028
2.10	12.3	1.596
2.10	15.2	1.331
2.18	13.5	1.852
2.17	12.6	1.869
1.96	16.3	0.926
2.13	13.8	1.719
2.23	11.9	1.772
2.15	13.3	1.640
2.18	12.6	1.940
2.20	13.2	2.134
2.10	15.5	1.667

Table 18 — Mix proportions for cemented-mine tailings and compressive strength development (21)

Mix	Mix No. 1 slag	Mix No. 2 slag	Mix No. 3 slag
Compressive Strengths, MPa			
7 days (strength not adequate for testing)	—	—	—
28 days	2.2	2.3	2.5
	2.1	2.1	2.4
	1.9	2.3	2.5
Average	2.1	2.2	2.5
90 days	1.63	1.62	1.66
	1.66	1.68	1.68
	1.59	1.67	1.69
Average	1.63	1.66	1.68
Slag 4000 Blaine, kg	0.100	0.232	0.300
Type 10 cement, kg	0.100	0.116	0.100
NRT tailings, kg	2.300	2.552	2.100
Water, kg	0.750	0.870	0.750

Note: Absolute volume replacement not adopted.

Mix No. 1: 4% slag 4000 Blaine and 4% Type 10 portland cement.
Mix No. 2: 8% slag 4000 Blaine and 4% Type 10 portland cement.
Mix No. 3: 12% slag 4000 Blaine and 4% Type 10 portland cement.

Table 19 — Cemented rockfill mix proportions and compressive strength development of rockfill (21)

Compressive Strengths	
7 days (Strength not adequate for testing)	
28 days	1.04
	1.14
	0.88
Average	1.02
90 days	1.59
	1.88
	1.72
Average	1.73
Mix	
KCCG 3000, kg	3.27
ASTM Type 10 cement, kg	2.18
Fine rockfill, kg	27.27
Coarse rockfill, kg	81.82
Water, kg	5.46

Notes: 1. Some places of segregation observed for test cylinders.
2. Absolute volume replacement not adopted.

Table 20 — Compressive strength at 28 days of mortar cubes cured at 38°C with 20, 35, 50, and 70% absolute replacement of portland cement by slag (21)

	Lead (N.B.) granulated	Nickel (Ont.) air-cooled	Nickel (Ont.) quenched	Copper (Ont.) granulated	Copper (Ont.) quenched	Copper (Que.) air-cooled	Copper (Que.) air-cooled	Copper (Que.) quenched	Copper (Que.) granulated
CONTROL	29.6	29.6	29.6	29.6	29.6	29.6	29.6	29.6	29.6
20%									
2000 MPa	21.4	22.5	17.1	16.0	20.7	20.8	21.7	19.3	20.2
3000	22.7	24.0	20.9	23.4	23.6	22.1	25.2	23.9	20.6
4000	30.5	24.8	23.8	25.4	25.8	24.6	26.5	25.7	24.6
5000	32.3	30.2	26.3	NG	27.5	25.0	30.8	27.6	26.2
35%									
2000 MPa	14.7	18.9	16.4	14.2	17.0	14,6	17.2	15.1	16.6
3000	16.1	21.5	19.7	20.4	21.3	19.8	23.7	21.5	20.8
4000	28.5	24.5	23.0	20.3	22.5	20.8	25.3	23.8	23.5
5000	30.0	29.1	25.9	NG	24.1	24.6	30.3	25.3	24.3
50%									
2000 MPa	13.7	18.3	13.9	9.5	13.8	11.3	14.6	13.4	13.3
3000	15.0	19.1	17.3	15.5	18.0	18.0	22.7	20.2	17.3
4000	20.6	21.4	20.9	17.8	18.8	19.7	23.9	23.6	21.3
5000	22.3	28.7	25.4	NG	19.6	23.3	26.9	24.4	22.0
70%									
2000 MPa	7.3	11.9	7.8	7.2	9.7	7.0	11.5	9.7	9.6
3000	7.9	12.8	12.1	8.5	12.8	10.5	14.5	12.5	11.7
4000	8.5	17.1	13.0	9.1	13.4	13.9	17.5	16.0	14.7
5000	10.8	19.8	16.8	NG	15.5	15.6	21.0	20.4	18.8

Notes: 1. Portland cement meets requirements of CSA Type 10.
2. Nominal Blaine fineness of slags indicated — 2000, 3000, 4000, and 5000.
3. All compressive strengths in MPa.
4. NG indicates slag was not ground to this fineness.

Table 21 — Compressive strength at 23°C of mortar cubes with 50% absolute volume replacement of portland cement by slag (21)

		Lead (N.B.) granulated	Nickel (Ont.) air-cooled	Nickel (Ont.) quenched	Copper (Ont.) granulated	Copper (Ont.) quenched	Copper (Que.) air-cooled	Copper (Que.) air-cooled	Copper (Que.) quenched	Copper (Que.) granulated
CONTROL	7D	31.3	31.3	31.3	31.3	31.3	31.3	31.3	31.3	31.3
	28D	36.8	36.8	36.8	36.8	36.8	36.8	36.8	36.8	36.8
2000										
days	1 MPa	7.0	3.9	4.8	4.6	4.7	3.1	3.3	4.3	3.8
	7	10.8	8.7	10.7	9.0	9.1	8.8	9.2	9.3	7.4
	28	19.1	14.2	17.8	19.0	17.0	12.0	14.4	16.2	13.8
	90	29.5	21.6	23.0	25.1	21.7	16.7	19.4	21.1	18.5
3000										
days	1 MPa	8.5	4.0	5.0	4.9	5.0	4.7	3.3	5.0	4.0
	7	12.4	8.8	10.8	10.3	11.0	10.9	9.5	12.6	8.6
	28	23.5	15.6	19.3	25.7	21.8	15.7	18.0	24.6	14.3
	90	37.9	26.0	26.1	29.7	26.5	20.6	25.9	32.0	24.3
4000										
days	1 MPa	12.1	4.1	5.2	5.6	6.3	5.0	4.3	5.6	4.7
	7	14.1	10.0	11.7	10.5	12.5	12.0	11.0	14.8	10.3
	28	29.8	17.5	21.7	26.7	24.8	19.2	20.5	30.5	21.6
	90	40.2	28.3	26.6	31.4	31.1	23.2	29.2	37.3	29.1
5000										
days	1 MPa	14.1	4.4	7.0	NG	7.5	5.1	4.5	5.9	5.3
	7	18.2	11.2	13.1		16.0	12.9	11.2	17.1	11.5
	28	28.7	25.0	26.2		30.4	21.3	24.2	35.2	25.9
	90	43.7	33.1	31.7		38.9	26.8	32.0	38.3	32.8

Notes: 1. Portland cement meets requirements of ASTM "Specifications for ground blast-furnace slag for use in concrete and mortars".
2. Nominal Blaine fineness of slags indicated — 2000, 3000, 4000, and 5000.
3. All compressive strengths in MPa, with flow indicated for each mix.
4. NG indicates slag was not ground to this fineness.

Table 22 — Gradations of coarse and fine aggregates for concrete mixes (21)

	Sieve size	Per cent passing	CSA A23.1 requirements per cent passing
Coarse aggregate	25.4 mm	100	100
	19 mm	95	90-100
	12.7 mm	52	30-75
	9.5 mm	36	20-55
	4.75 mm	2	0-10
Fine aggregate	9.5 mm	100	100
	4.75 mm	97	95-100
	2.36 mm	85	80-100
	1.18 mm	72	50-85
	600 μm	52	25-60
	300 μm	22	10-30
	150 μm	6	2-10

Table 23 — Compressive strength development of concrete mixes containing 50% ground non-ferrous slags incorporated by absolute volume replacement (21) of CSA Type 10 portland cement

Mix Mix details	A 3000	A 4000	B 3000	D 4000	D 3000	E 4000	G 3000	G 3000	H 4000	H 3000	I 4000	MICG 4000 (Foreign)	CONTROL 1	CONTROL 2	CONTROL 3 (Used as control)
Ground non-ferrous Slag, kg	8.32	8.32	7.36	7.36	8.09	8.09	7.04	7.31	7 31	4.77	4.77	6 54	—	—	—
Type 10 cement, kg	6.54	6.54	6.54	6.54	6 54	6.54	6.04	6.54	6 54	4 45	4 45	6 04	13 09	13.09	13.09
Fine aggregate, kg	38.41	38.41	38.41	38.41	38.41	38.41	35 54	38.41	38 41	26 05	26 05	35.54	38.41	38.41	38.41
Coarse aggregate, kg	52.86	52.86	52.86	52.86	52.86	52.86	48.96	52.86	52 86	35 91	35 91	48.96	52 86	52.86	52.86
Water, kg	7.28	7.28	6.82	6.82	7.17	7.17	6.41	6 80	6.80	4.50	4 50	6.18	6 46	6.46	6.46
WRA, mL	—	—	—	—	—	—	—	—	—	—	—	—	60.7 (Mulco A)	60.7 (Mulco A)	60.7 (Mulco A)
Slump, mm	130	130	75	75	110	120	50	70	100	55	50	65	45	40	70.0
Air, %	1.5	1.5	2.2	1.9	1.5	1.9	1.7	1.5	1 4	1.9	1 9	1.9	3 9	3.2	3.4
Temperature, °C	20	19	20	20	20	20	20	20	20	20	21	20	20	21	19
Bulk density, kg m³	1937	1963	1949	1923	1958	1953	1937	1958	1968	1930	1940	1928	1928	1977	1958
Compressive strengths, MPa															
7 days	9 5 9.3 10.0	12 4 11.9 12.1	9 2 9.2 9.7	10.7 10.2 10.7	9 9 9.4 9.5	10.2 11.1 10.4	10.7 10.5 10.7	9 7 9 6 9.4	9 2 9.2 9.5	10 7 11 0 11.0	13.8 14 0 13.8	11 0 11.2 11 5	27.6 27.3 28.1	32.0 31.0 32.0	29.2 29.8 28.3
Average	9.6	12.1	9.4	10.5	9 6	10.6	10.6	9.6	9 3	10 9	13 9	11.2	27.7	31.6	29.1
28 days	23.7 21.4 21.7	28.5 27.3 30.3	16.8 17.3 16.8	20.1 20.4 20.9	22.4 22.4 21.9	24 7 24 7 26.0	21.4 21.7 21.2	17.3 19.4 18.4	18.4 18.9 18 9	23 4 23.2 24 0	27.5 27.0 26 3	24 5 26 0 24.5	35.6 35.9 —	40.8 41.0 40.5	37.4 37.9 38.1
Average	22.2	28 7	17.0	20.5	22.2	25.1	21.4	18.4	18.6	23.5	26.9	25 0	35.8	40.8	37.8
90 days	32 6 35.6 35.7	40.8 39 7 42 8	23 4 24.0 22 9	28 5 28 0 27 0	28 0 28 0 27.5	28 5 30 1 29 6	31.6 30.1 31 1	24 5 25 5 24 5	24 0 25 0 26 0	27 5 27 5 27 0	31 1 31 2 31 1	30 6 30 1 31 1	42 2 42 3 —	49 0 47 3 47.7	45.4 44.2 44 5
Average	34.6	41.1	23.4	27.8	27.8	29.4	30.9	24.8	25.0	27.3	31.1	30.6	42 2	48.0	44.7

Note: All mixes and test in accordance with CSA A23.1 and CSA A23.2, respectively. 100 mm Φ by 200 mm cylinders for all mixes except CONTROL 1 (150 mm Φ by 300 mm cylinders).

Table 24 — Compressive strength development of concrete mixes containing 50% ground non-ferrous slags incorporated by absolute volume replacement of Type 10 portland cement, with water-reducing admixtures (WRA) (21)

Mix Mix details	B 3000 WRA	B 4000 WRA	C	C WRA	F 4000 WRA	G 3000 WRA
Ground non-ferrous slag, kg	7.36	7.36	7.14	7.14	7.77	7.32
Type 10 cement, kg	6.54	6.54	6.54	6.54	6.54	6.54
Fine aggregate, kg	38.41	38.41	38.41	38.41	38.41	38.41
Coarse aggregate, kg	52.86	52.86	52.86	52.86	52.86	52.86
Water, kg	6.46	6.46	6.46	6.46	6.46	6.46
WRA, mL	64.5 (TCDA A)	64.5 (TCDA A)	—	63.5 (Mulco A)	66.4 (Mulco A)	64.3 (TCDA A)
Slump, mm	110	90	40	90	90	90
Air, %	4.0	3.3	2.5	5.3	3.3	3.7
Temperature, °C	21	21	20	22	21	21
Bulk, density, kg/m³	1967	1936	1954	1913	1937	1967
Compressive strengths, MPa						
7 days	12.2 12.2 11.7	12.0 11.7 12.4	14.8 13.8 13.8	14.8 14.8 14.0	15.0 14.5 14.8	11.2 11.7 11.7
Average	12.0	12.0	14.1	14.5	14.8	11.5
28 days	21.4 21.9 21.4	24.5 24.5 25.0	22.9 22.4 23.4	24.0 23.2 22.9	23.4 24.0 23.4	22.9 24.0 24.0
Average	21.6	24.7	22.9	23.9	23.6	23.6
90 days	30.6 29.6 29.1	31.1 31.6 21.1	31.1 30.1 20.1	30.1 31.1 31.2	27.8 28.8 28.3	30.6 31.6 31.7
Average	29.8	31.3	30.4	30.8	28.3	31.3

Note: All mixes and tests in accordance with CSA A23.1 and CSA A23.2, respectively, 100 mm Φ by 200 mm cylinders.

FIGURES

CANADIAN NON-FERROUS SLAGS FOR RESOURCE AND ENERGY CONSERVATION

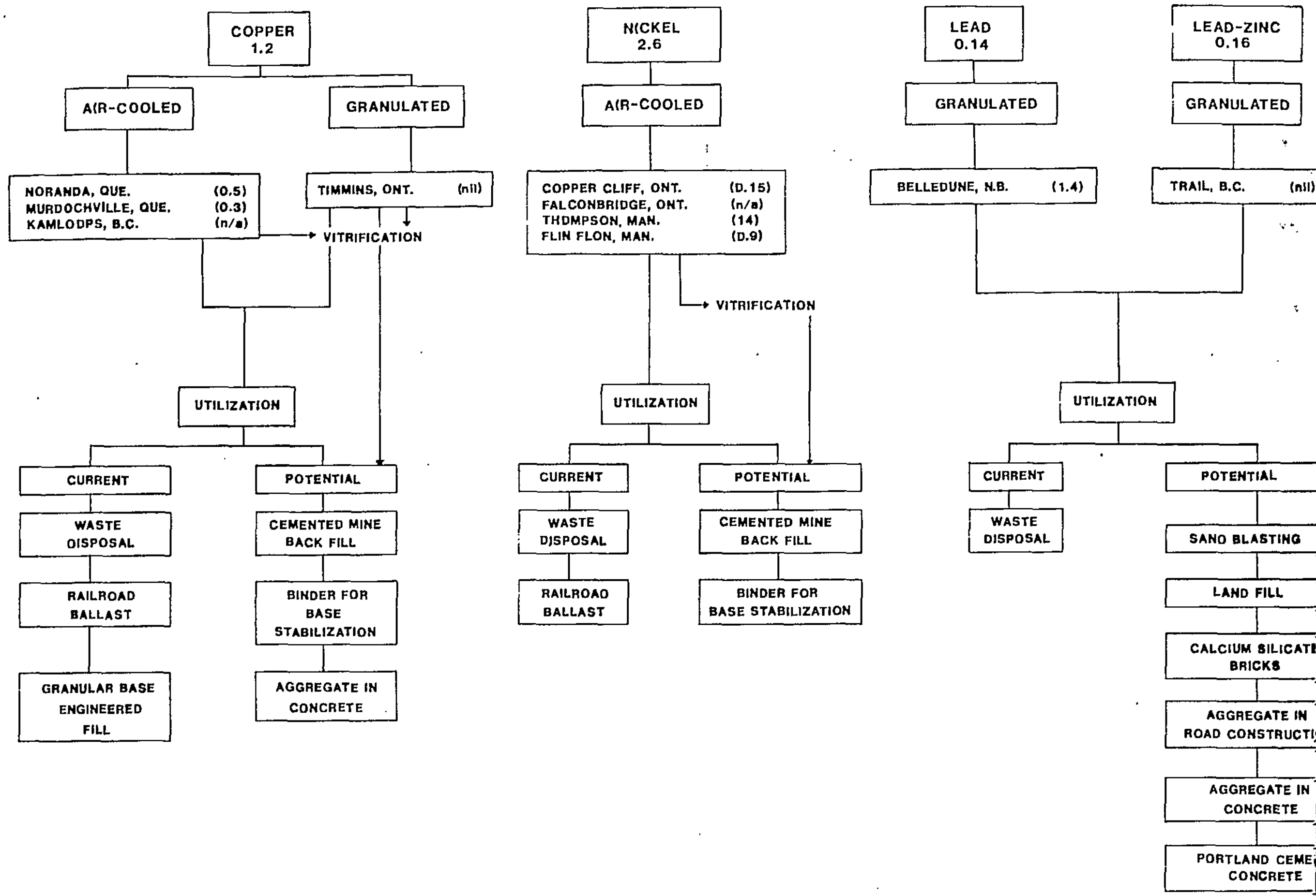

Fig. 1 — Production, location, and utilization of non-ferrous slags from Canadian sources (2)

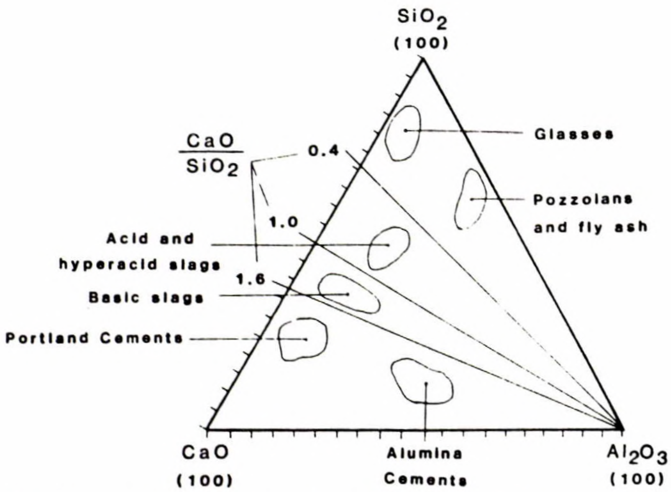

Fig. 2a — Representation of some cementitious materials in the system CaO-SiO_2-Al_2O_3

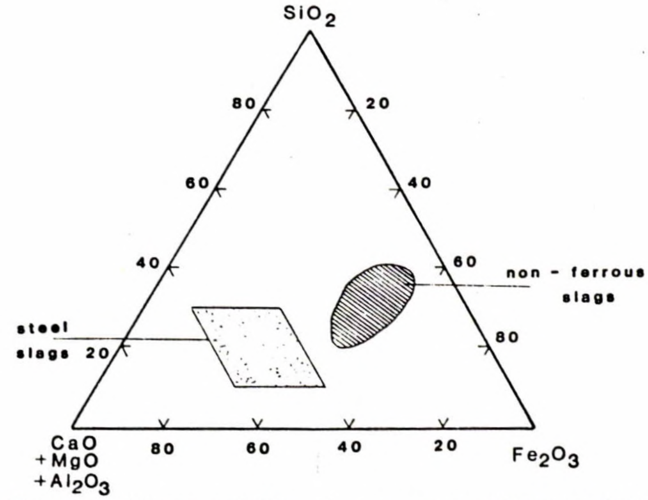

Fig. 2b — Representation of some cementitious materials in the system CaO-SiO_2-Fe_2O_3

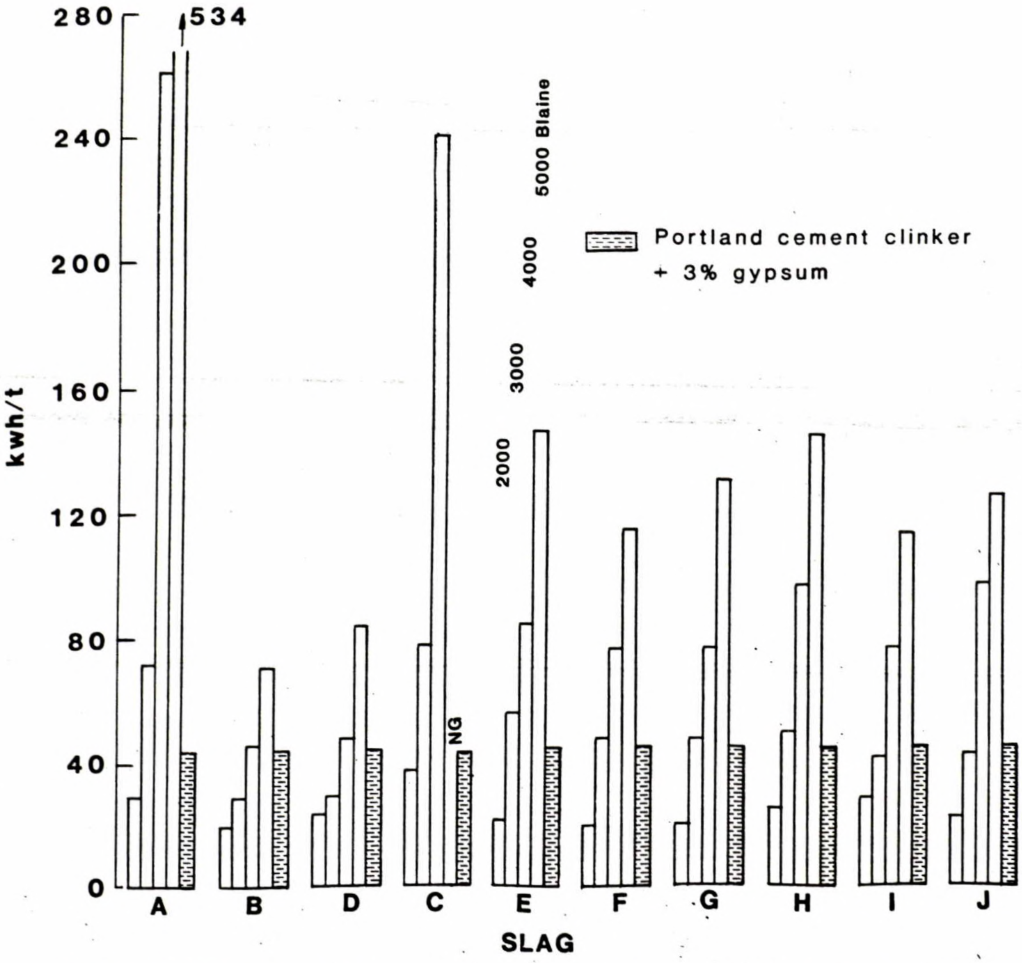

Fig. 3 — Energy consumption for production grinding of non-ferrous slags (10)

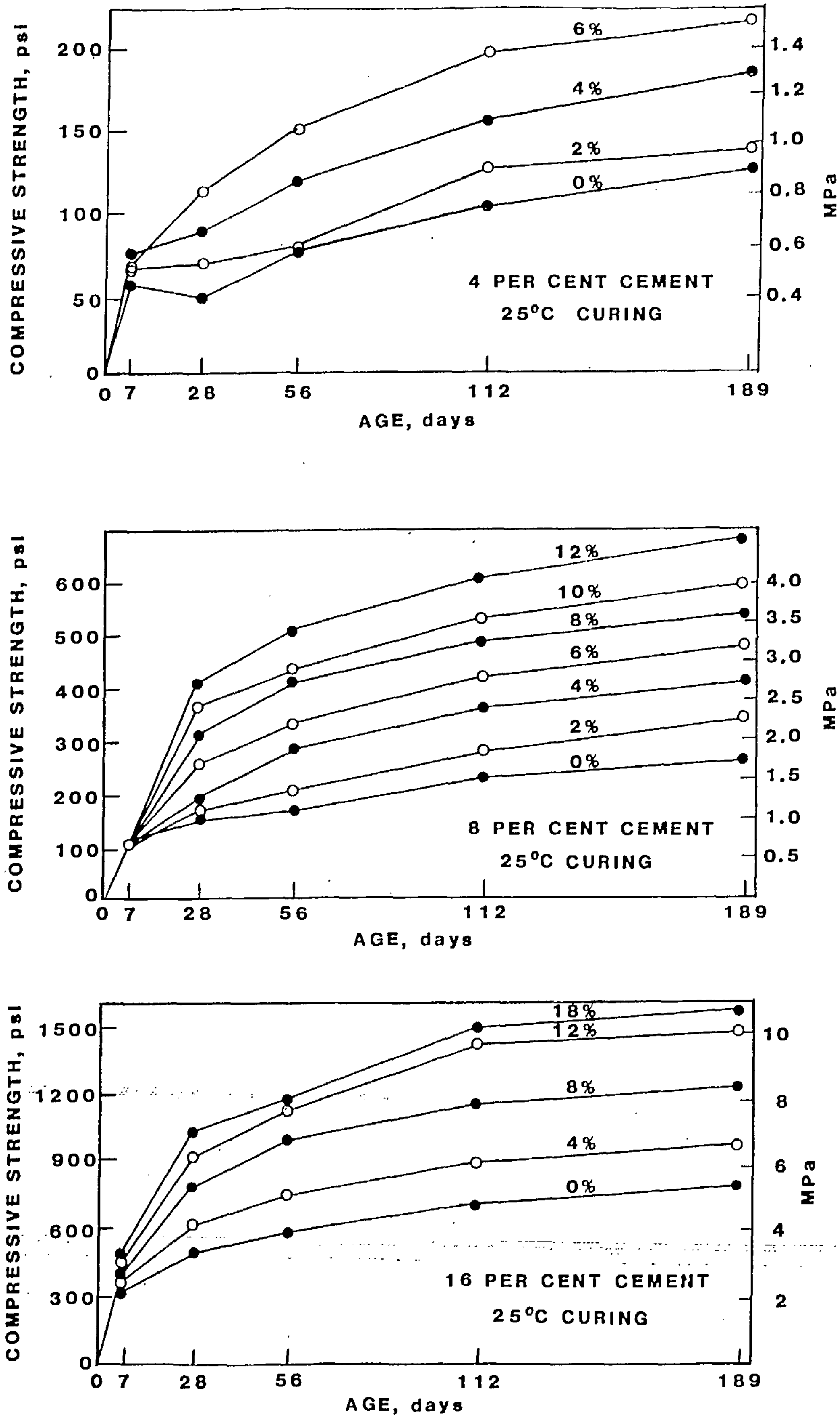

Fig. 4 — Curing curves demonstrating strengthening effect of ground copper reverberatory furnace slag acting as a pozzolan with different cement contents (3)

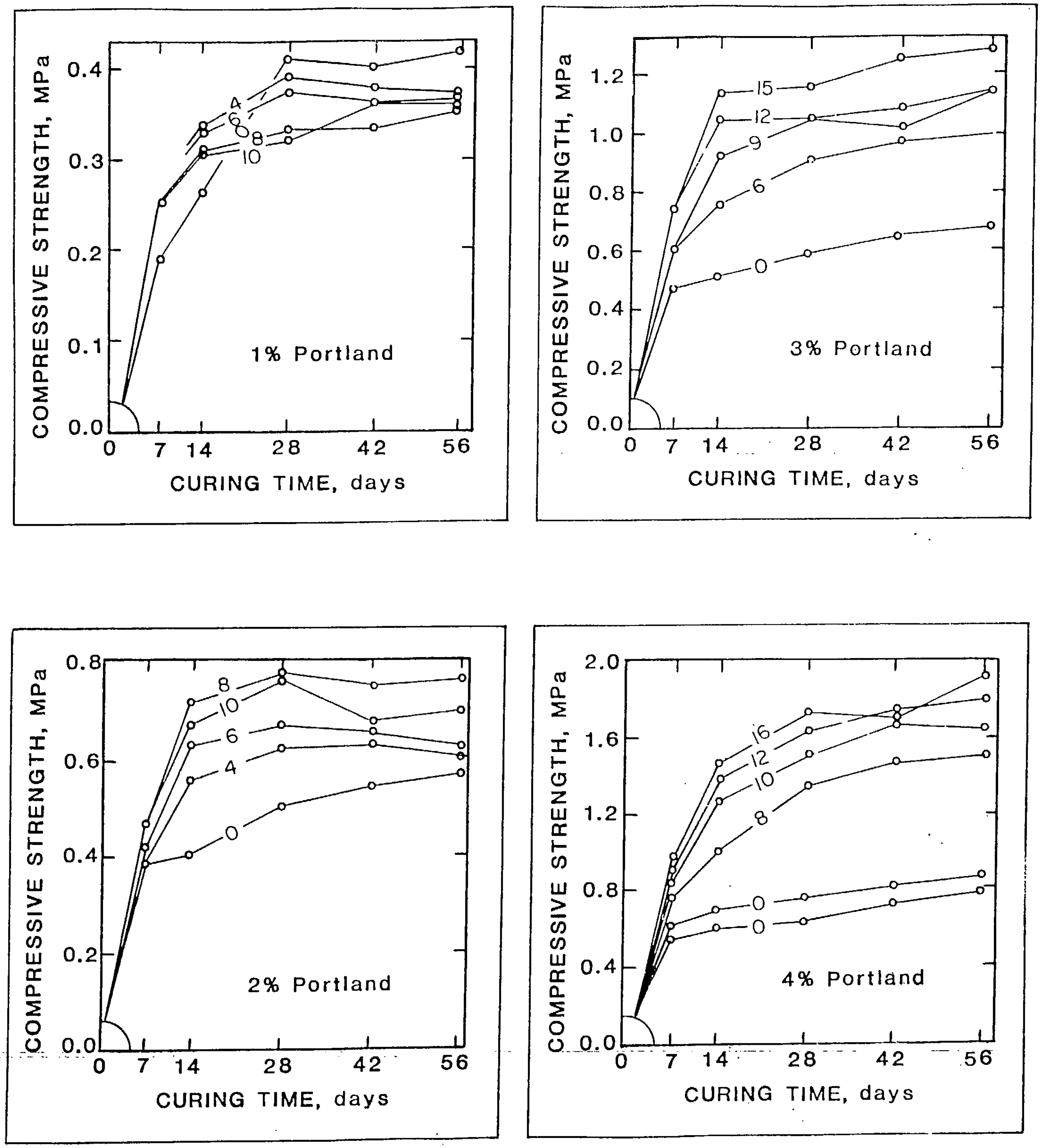

Fig. 5 — Curing curves at 1, 2, 3, and 4 wt % portland cement and various copper reverberatory furnace slag additions, as indicated on individual curves (6)

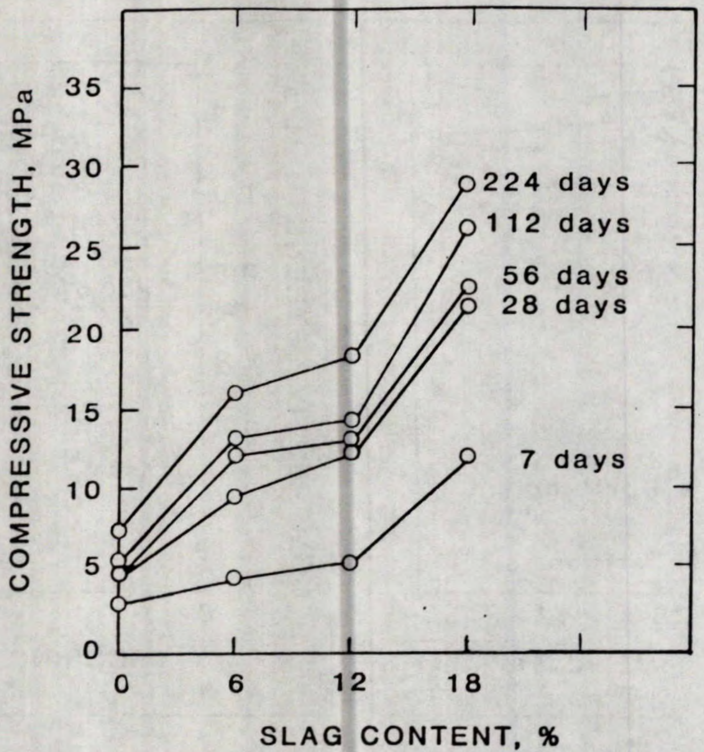

Fig. 6 — Effect of ground granulated slag on uniaxial compressive strength of consolidated fill containing 6% portland cement (12)

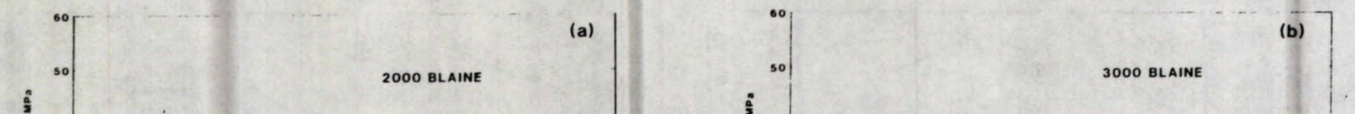

Fig. 7 — Compressive strength development at 23°C in moist-cured mortars containing 50% slag by absolute volume replacing portland cement (10)

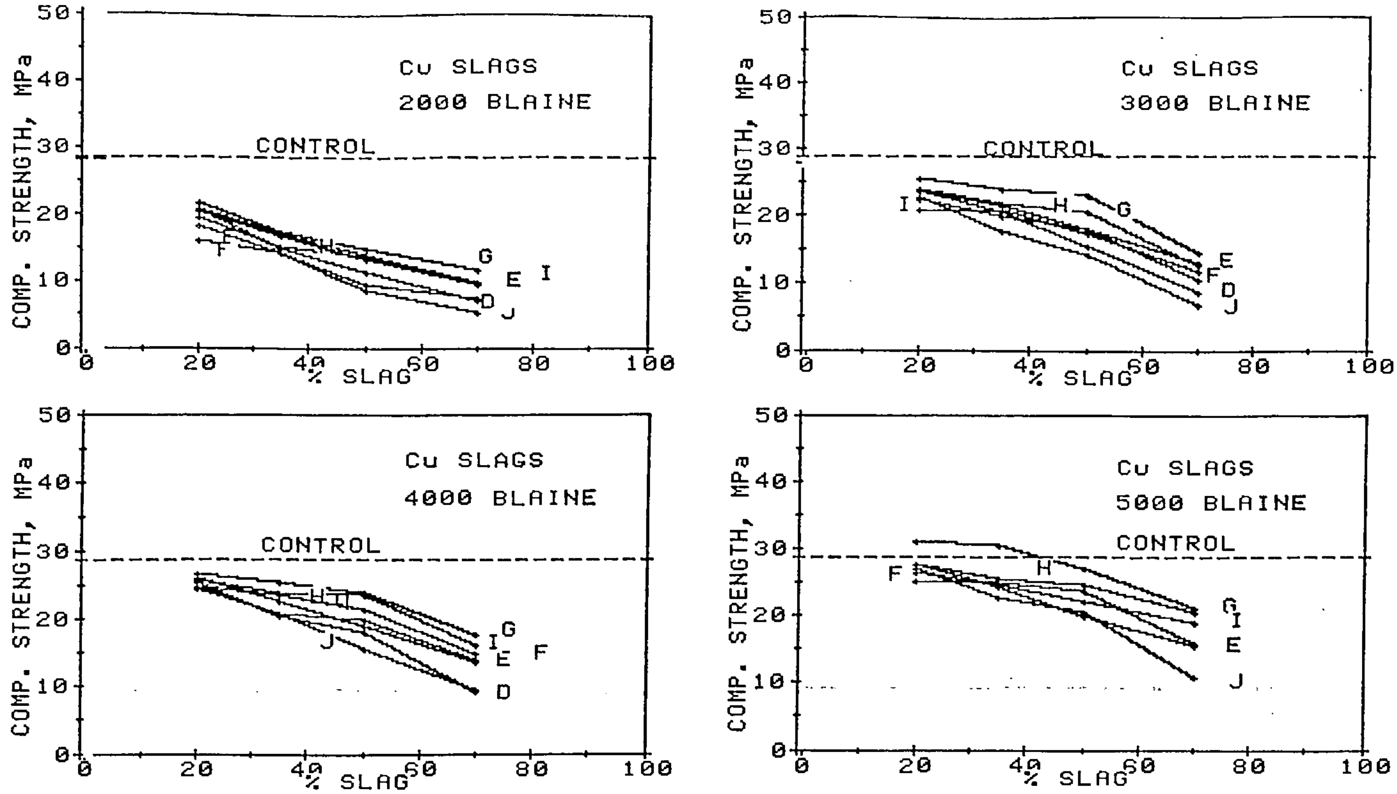

Fig. 8 — Compressive strength of copper slags-portland cement mortars at 28 days curing (10)

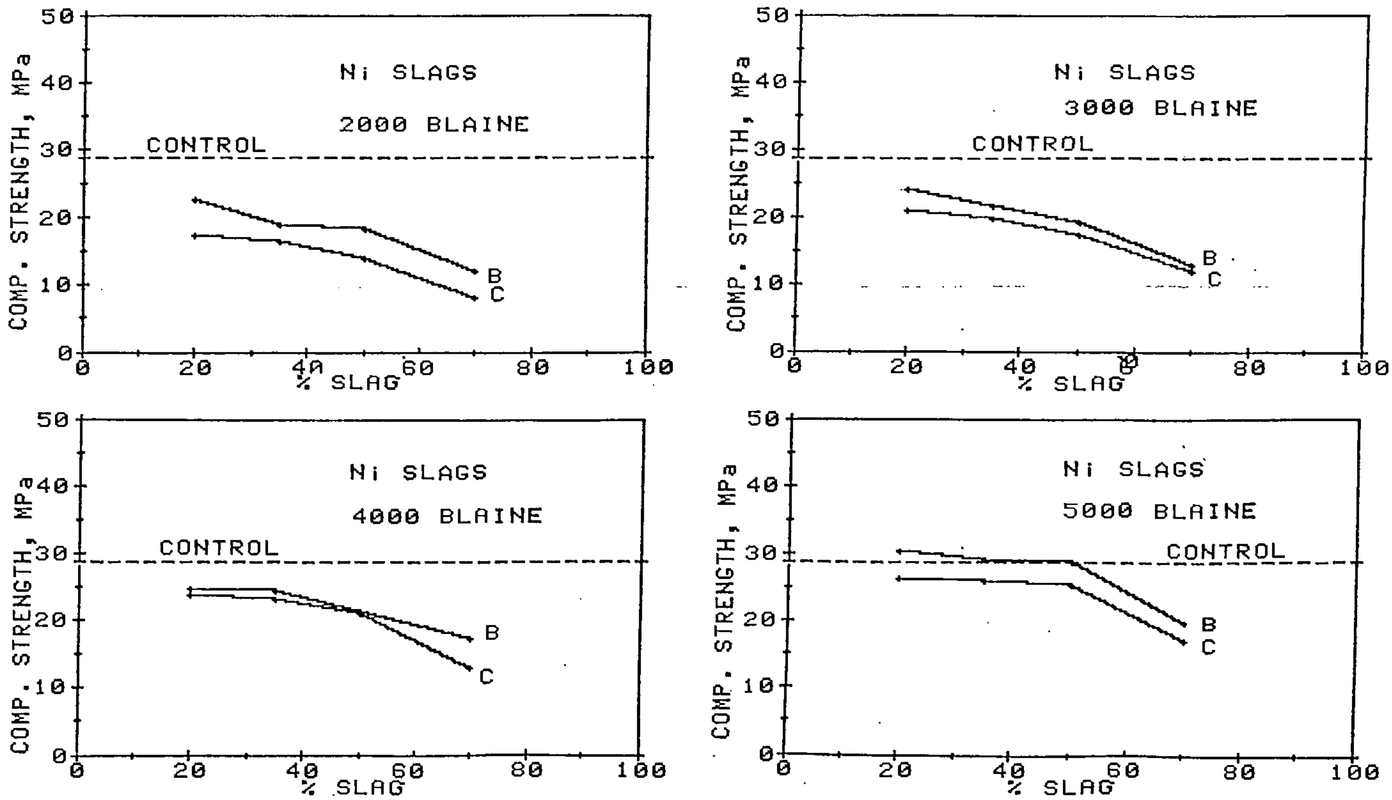

Fig. 9 — Compressive strength of nickel slags-portland cement mortars at 28 days curing (10)

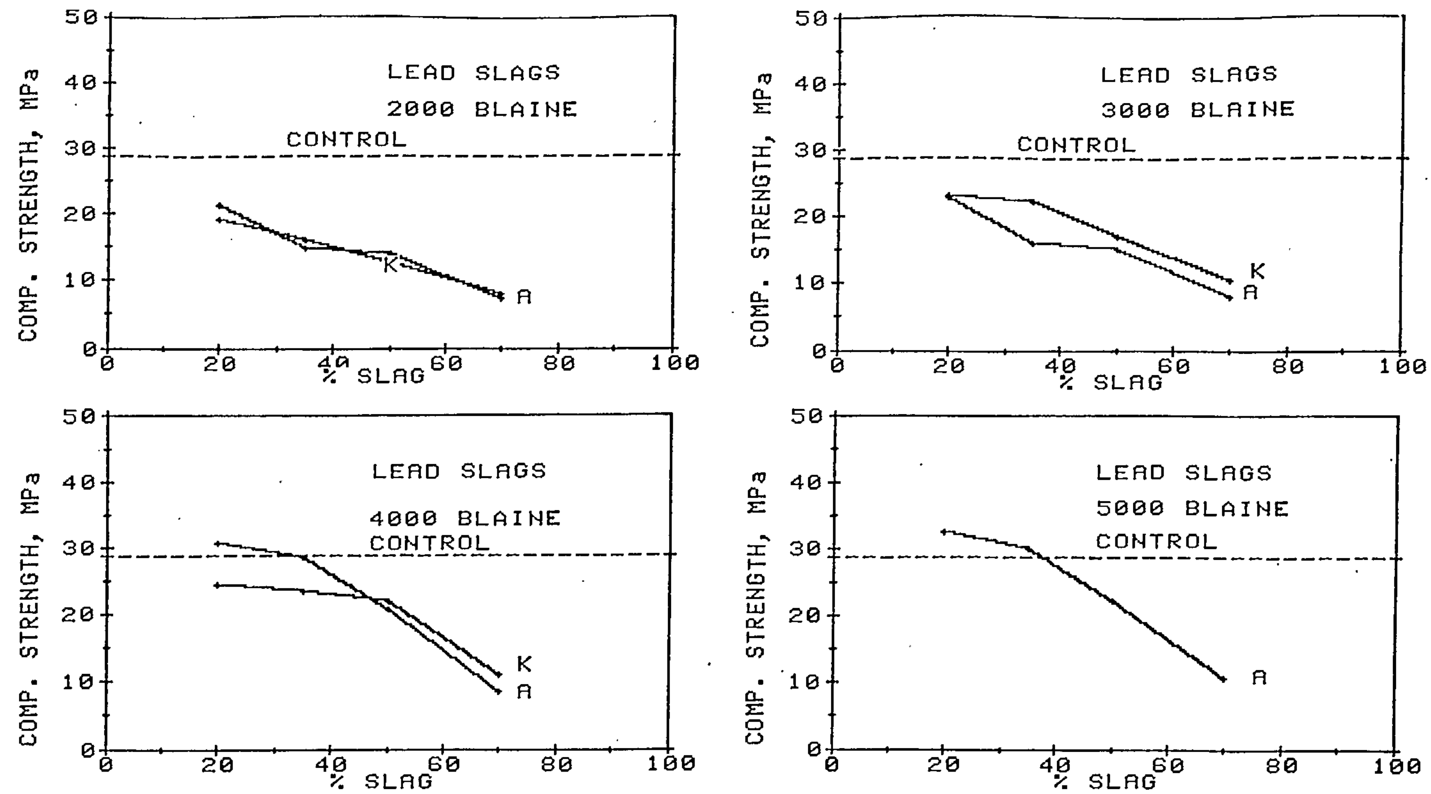

Fig. 10 — Compressive strength of lead slags-portland cement mortars at 28 days curing (10)

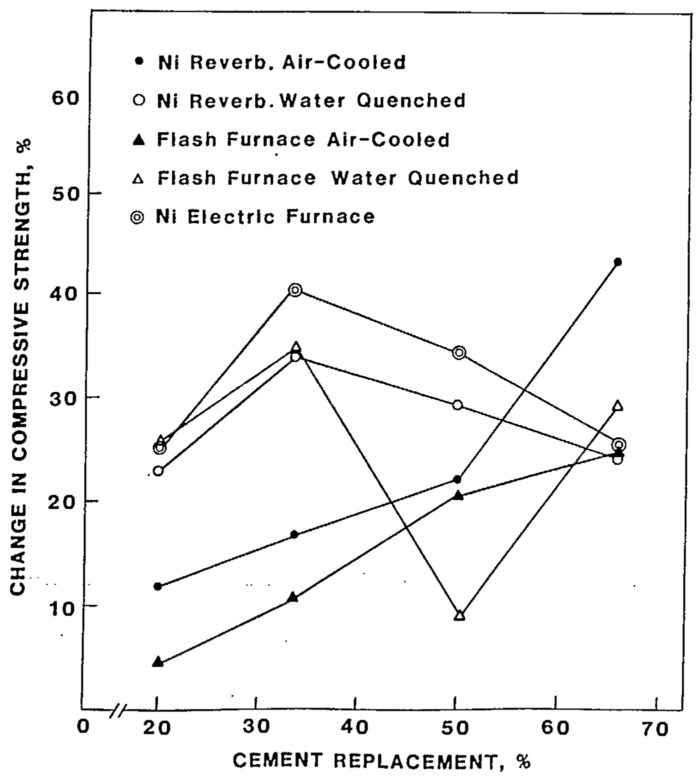

Fig. 11 — Change in strength at different curing ages calculated on basis of standard 4.8 wt % portland cement specimens cured to same age during pozzolanic testing at various cement replacement levels (20)

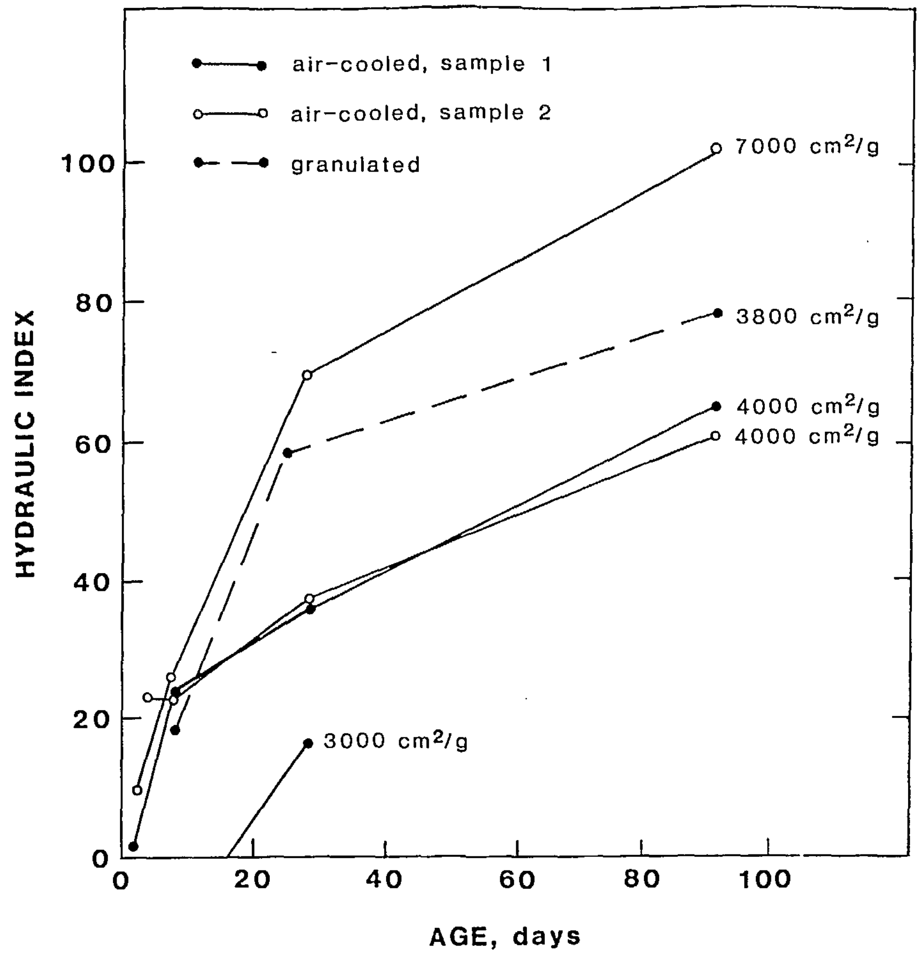

Fig. 12 — Hydraulic index of air-cooled and of granulated nickel slags of different fineness (5)

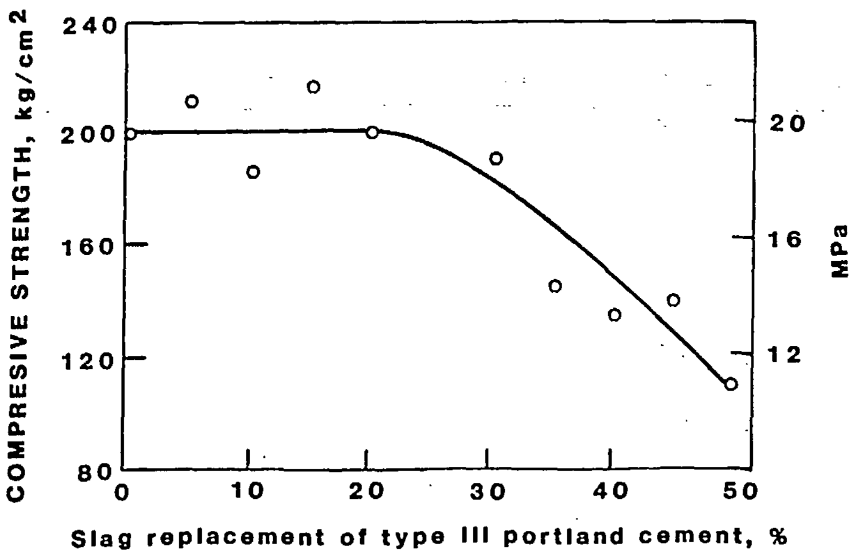

Fig. 13 — Compressive strength of Type III portland cement-lead slag binders at various cement replacement levels (7)

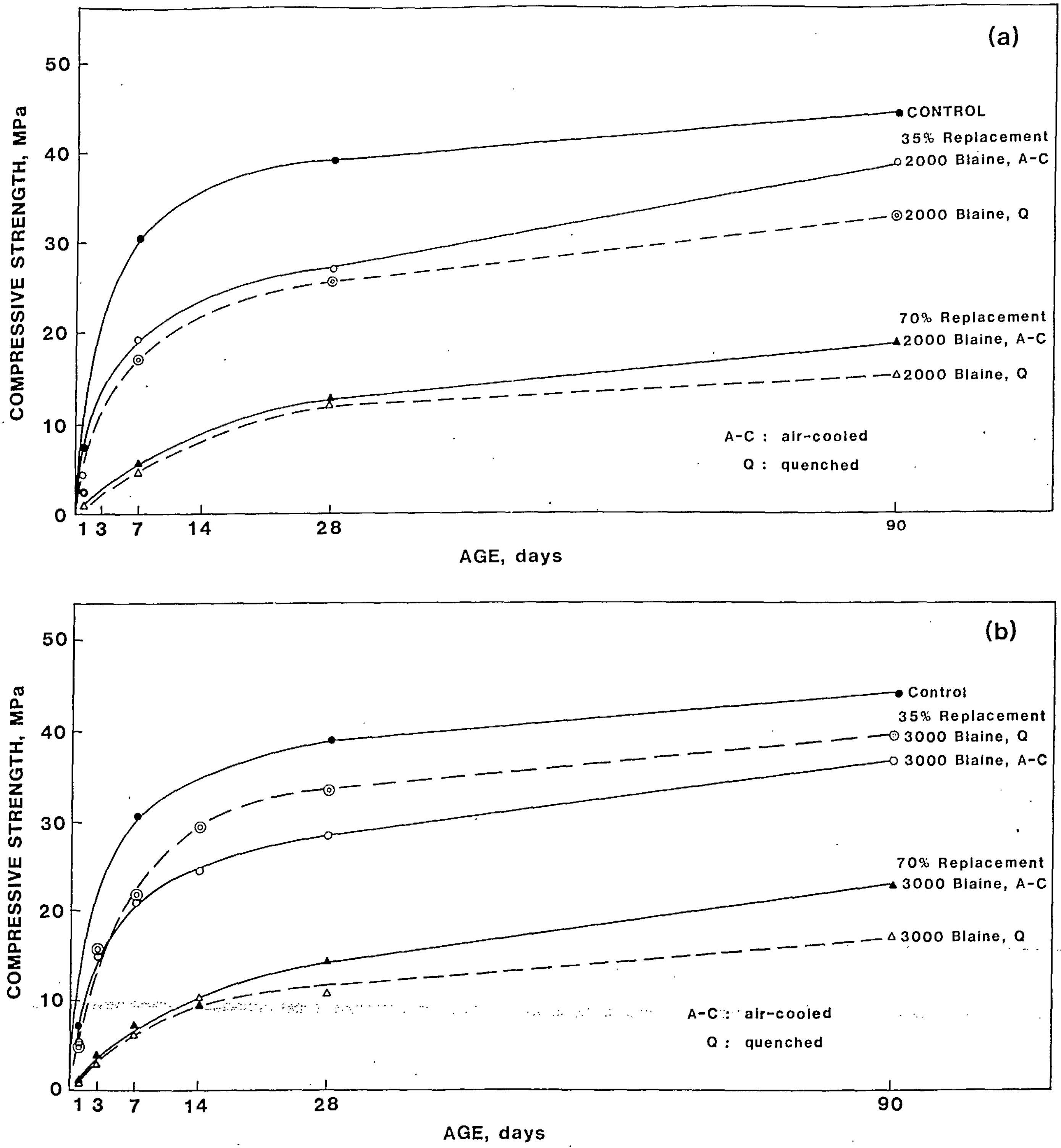

Fig. 14 — Strength development in portland cement-copper slag mortars cured at room temperature (15)

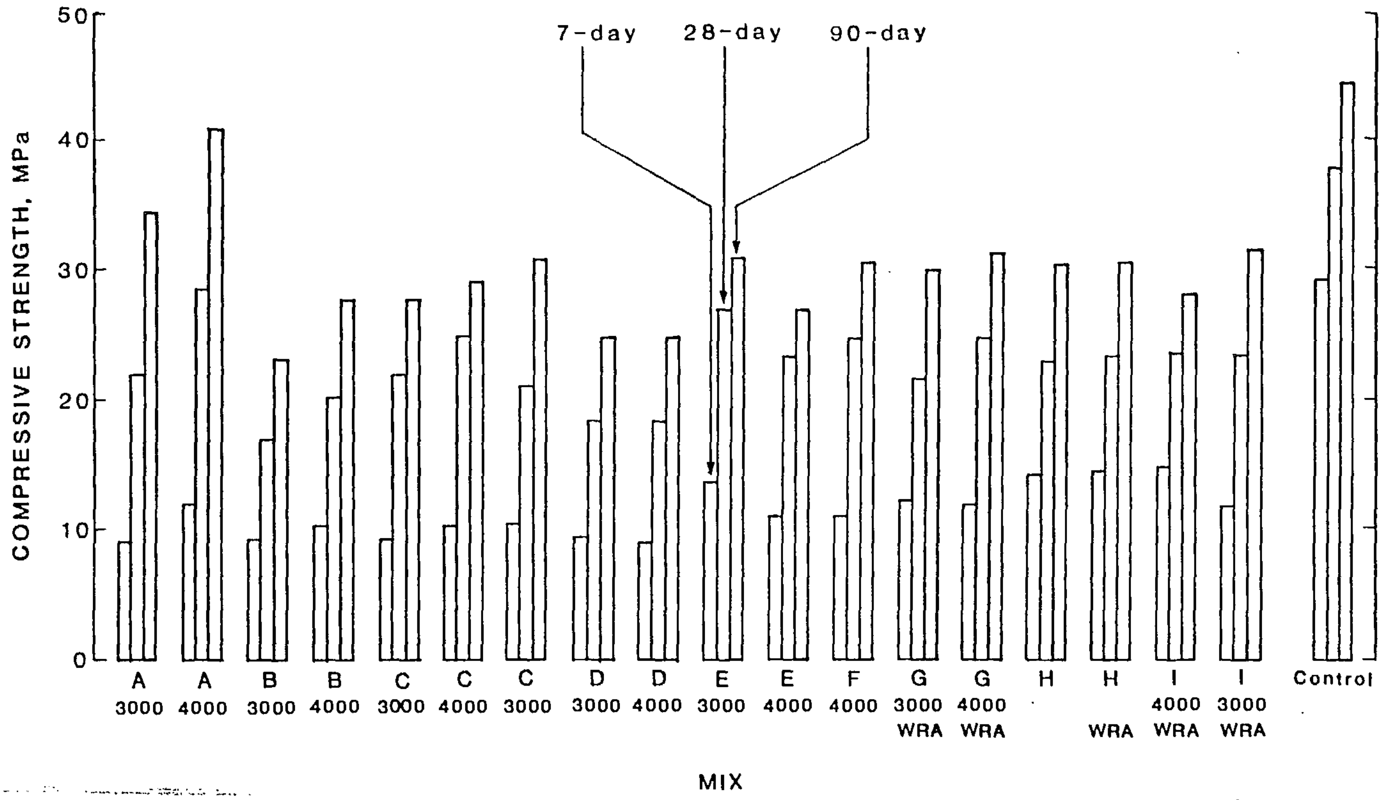

Fig. 15 — Compressive strengths of concrete mixes (21)

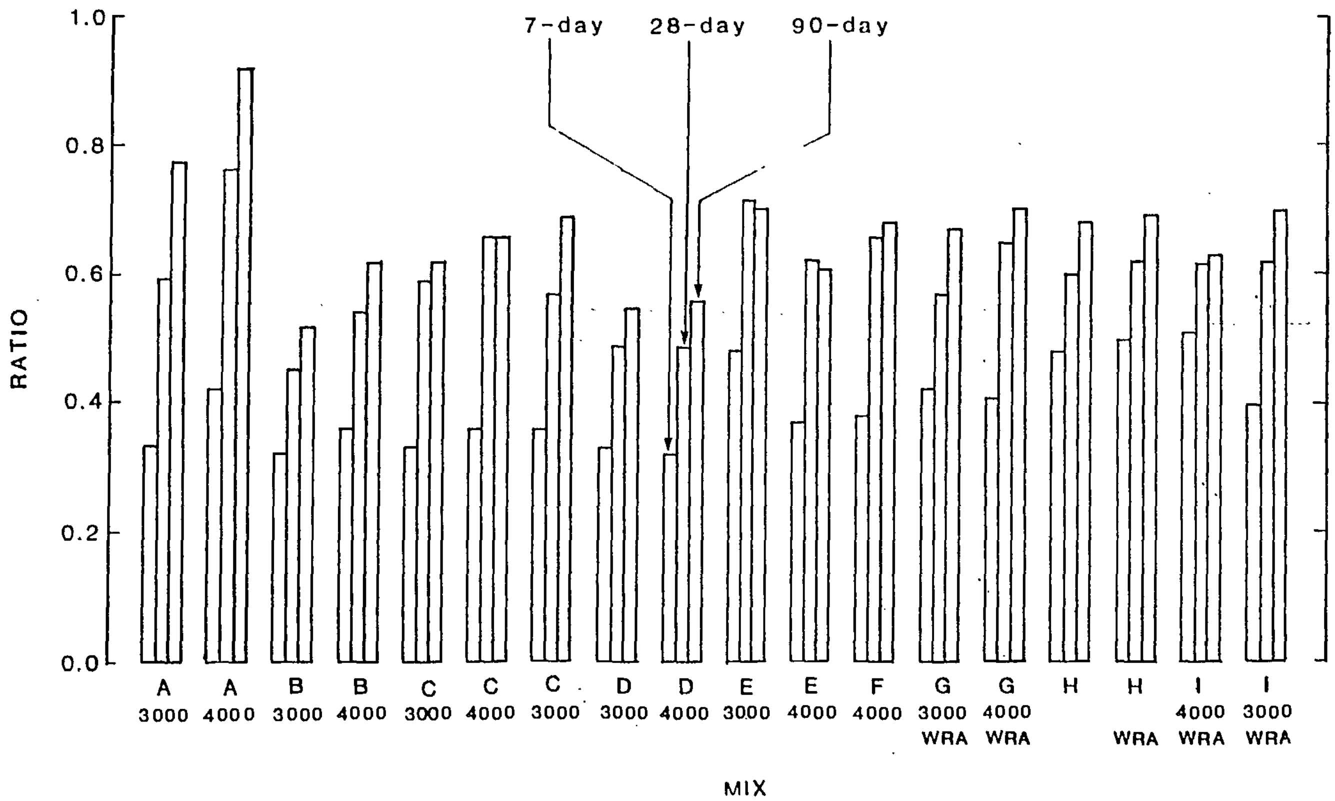

Fig. 16 — Compressive strength ratios of concrete mixes (21)

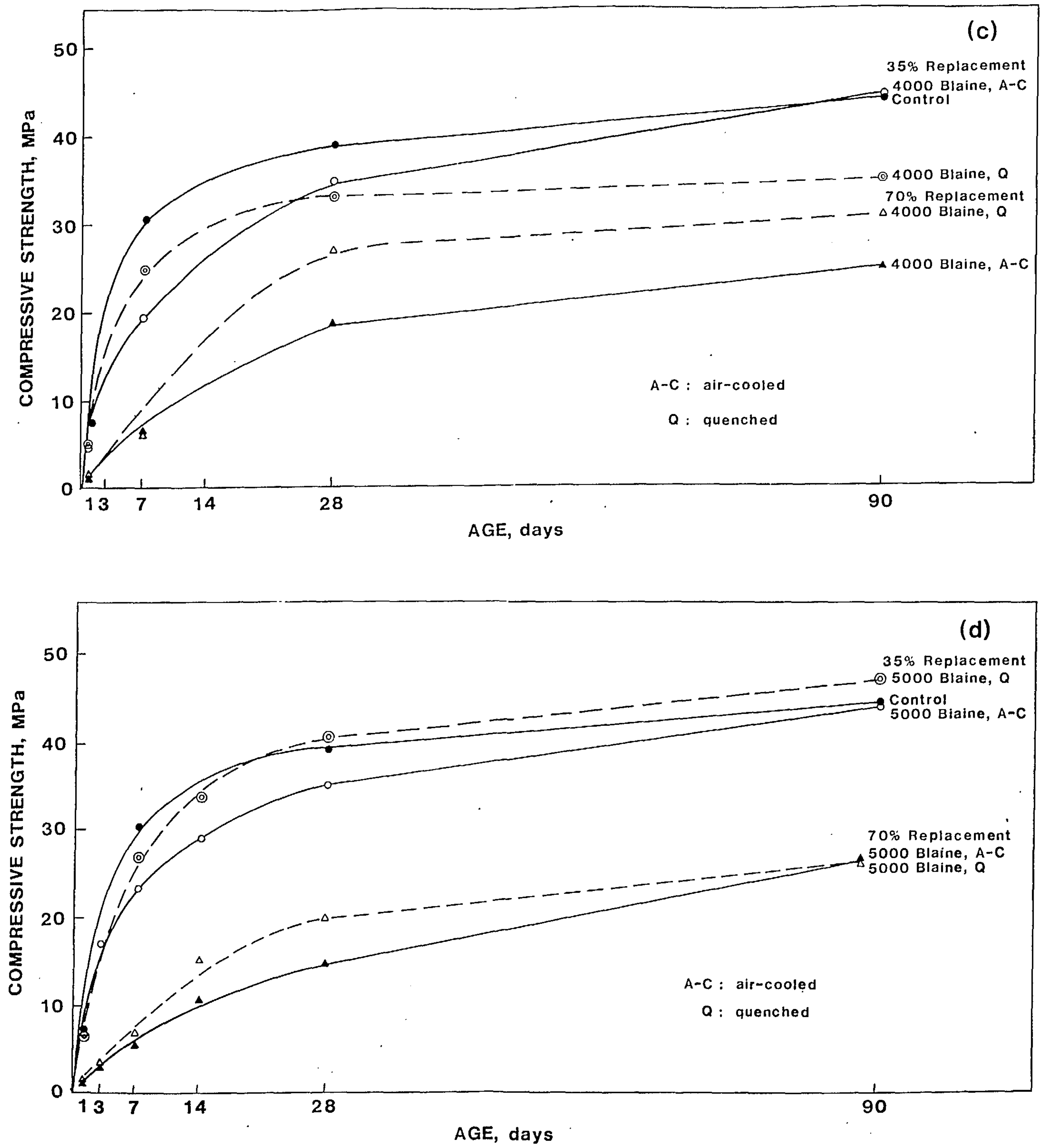

Fig. 17 — Strength development in portland cement-copper slag mortars cured at room temperature (15)
(c) slag ground to 4000 cm²/g (Blaine method)
(d) slag ground to 5000 cm²/g (Blaine method)

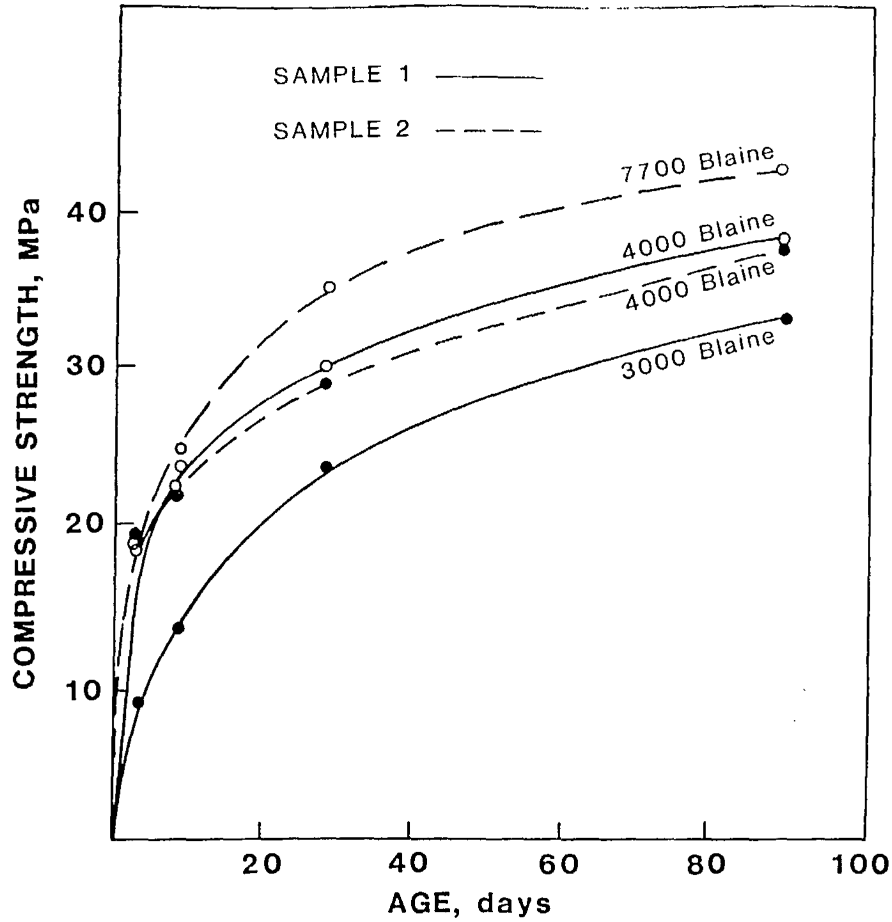

Fig. 18 — Effect of fineness on compressive strength of 70 wt % portland cement and 30 wt % air-cooled nickel slag binders (5)

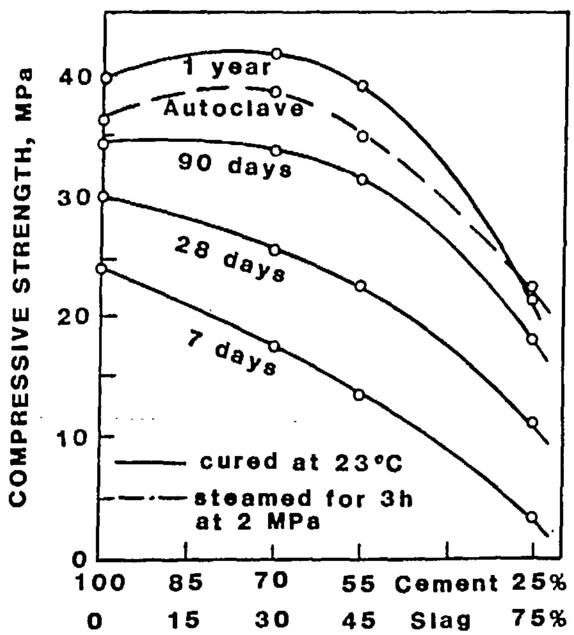

Fig. 19 — Effect of slag content of binders on compressive strength of mortar cubes (34)

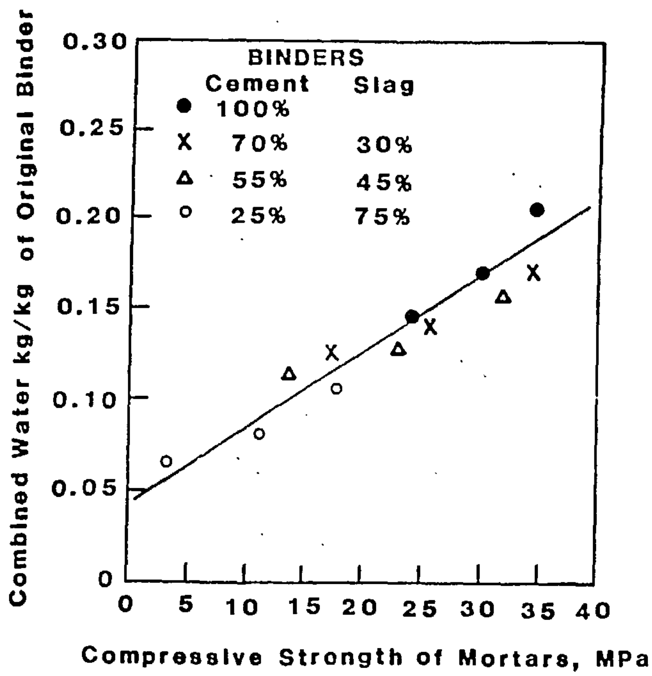

Fig. 20 — Relation between combined water and compressive strength (34)

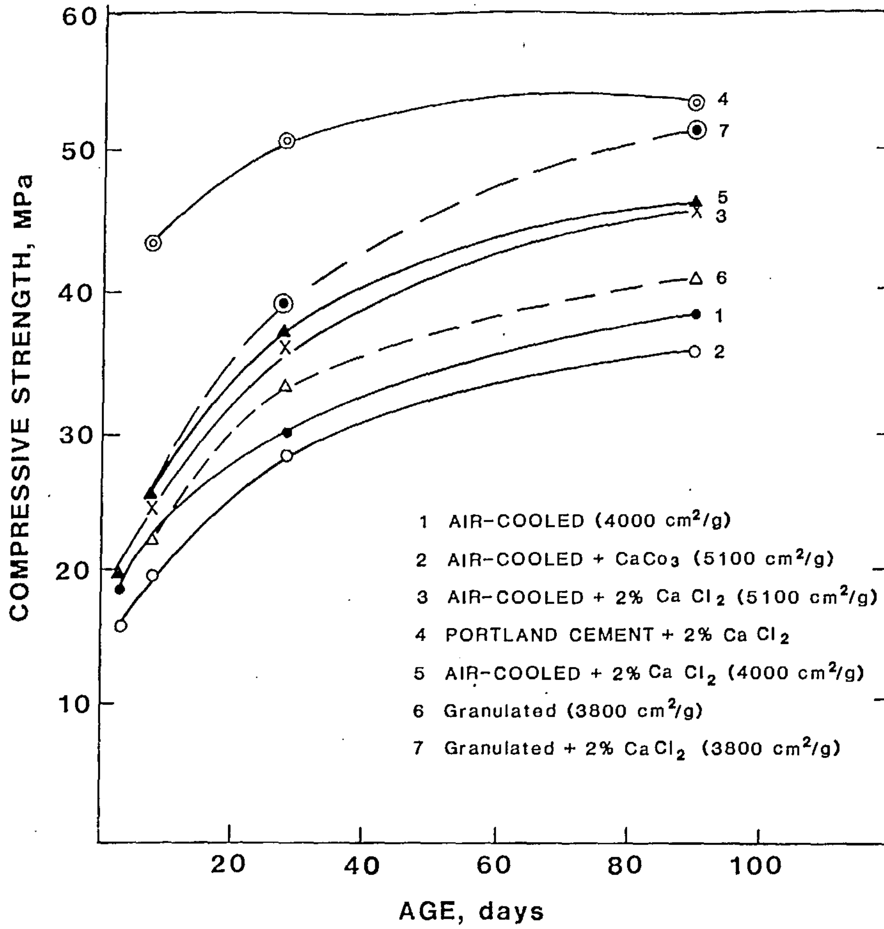

Fig. 21 — Effect of activators on compressive strength of air-cooled and granulated nickel slags ground to various finenesses (5)