

UTILISATION OF SLAGS FOR THE MANUFACTURE OF CEMENT

by P. R. Jochens, C. W. Wolluter and D. D. Howat

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Introductory remarks by author

Prof D. D. Howat (Member): I am a man with a grievance this afternoon. The other authors of the paper entered into a conspiracy to ensure that I presented the paper, and finally even had the audacity to say that this was the least that could be expected from me as I had done so little of the other work. Looking at the distinguished audience here that includes some figures who have forgotten more about cement than some of us have ever learned, I realise how right the other authors were. I feel very much cast in the role of the fool who was pushed in where angels fear to tread. I hesitate to say, Sir, that I would not use the word angels in any definition of the authors of this paper.

In presenting the paper, may I try to put forward a few simple points about cement that are probably as little known to the majority of the audience as they were to me—at least until very recently.

Concrete, made by mixing Portland cement, sand, crushed rock and water is the most widely used constructional material in the world. Generally the production of actual Portland Cement is about two-thirds that of steel and by the time this is formed into concrete the total is about five times the world tonnage of steel produced.

A very rough approximation suggests that world consumption of concrete is about one ton per person per annum. Apart from fresh water mankind consumes no other material in such quantities.

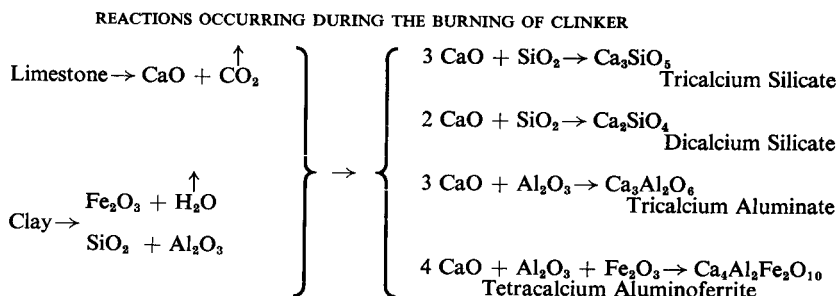
What mankind originally required was a mortar to be used for joining blocks of stone or bricks. Such mortar was originally made from limestone burned in a kiln and then mixed with water. Production of mortar of this type began over 5,000 years ago. Some samples from pyramids in Egypt have shown this mortar to be in good condition although over 4,500 years old.

The progress of technological development was very slow until 1824 when an English bricklayer, Joseph Aspidin, patented a new mortar material which he made by burning limestone and clay together in his kitchen stove. Aspidin called his product 'Portland Cement' because, in colour, it resembled a well-known building stone quarried in the Isle of Portland on the south coast of England.

Aspid's same types of raw materials are used today in modern cement production and the product is still referred to as Portland cement. A lime-containing material such as chalk or shell and a clay-type material such as shale, slate or clay itself, are mixed in the required proportions, ground and fed to a kiln where the minimum burning temperature is about 1,500°C. The raw materials react to form hard chunks of a material known as 'clinker'. About 5 per cent of gypsum is added to the clinker and the mixture is then ground to a very fine powder, the function of the gypsum being to control the rate of setting of the concrete.

The key oxides in cement production are lime, silica, alumina and iron oxide. The possible reactions occurring during and the products of the burning process are shown in Table I.

TABLE I

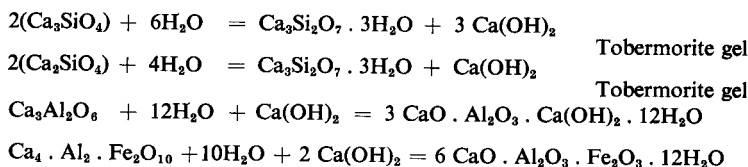


The notable feature of cement clinker is that several of these compounds are clearly visible and identifiable under the microscope, being embedded in a glassy matrix, which comprises various quantities of the oxides present.

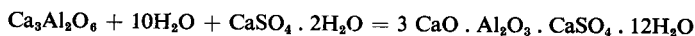
The essential reactions which occur when a cement sets are believed to be something along the lines shown in Table II.

TABLE II

POSSIBLE REACTIONS IN THE SETTING OF CEMENT



EFFECT OF GYPSUM



Of these reactions those resulting in the formation of the so-called Tobermorite gel are the more important, as this product is the main cementing agent in concrete.

Obviously a material produced in such vast quantities—as cement—must be relatively low priced and the essential raw materials be reasonably easily and widely available.

For many years interest has been focussed on slags produced in various iron smelting processes as possible materials for the manufacture of cement. Invariably such slags contain silica, alumina, lime and magnesia. In addition during the formation of the slags reaction has already occurred among the various oxides so that the expensive step of 'burning the clinker' may be eliminated. Further these slags are produced in plants which are frequently within densely populated areas which are large potential consumers of cement.

Obviously chemical composition must play a very important role in assessing the value of a slag as a raw material for cement. Table III shows rough analytical data for Portland Cement, iron blast furnace slag produced by Iscor and a slag from a ferro-alloy plant.

TABLE III

COMPOSITIONS OF PORTLAND CEMENT AND SLAGS (PERCENTAGES)

Oxide	Portland cement	Iscor B.F. slag	Ferro/Alloy slag
SiO ₂	22	36	29
Al ₂ O ₃	6	10	16
CaO	64	38	43
MgO	5	16	12
	} 69	} 54	} 55

The composition of slag is determined first by the composition of the ore and coke used, and second by the metallurgical considerations, e.g., those relating to melting point and viscosity imposed by the smelting process.

Further extensive work on the exploitation of slags for the manufacture of cement has shown that certain physical characteristics of the slag are of paramount importance. Reference was made to the presence in the cement clinker of clearly defined crystalline phases such as the di- and tri-calcium silicates and calcium aluminates. These compounds are embedded in a matrix of glass, which normally constitutes a relatively small proportion of the total solid material.

Extensive work on the use of these slags has revealed a rather strange anomaly. If slags are to be successfully employed for cement manufacture they must contain a minimum of 85 per cent glass. The ratio of 85 glassy phase to 15 crystalline material is probably the inverse of a typical cement clinker. Any assessment based on the chemical analysis of the slag must be supplemented by the determination of the glass content.

Production of a slag in a glassy state is only possible if the crystallization potential is relatively low so that at the rates of cooling obtaining in a granulation plant the slag is predominantly glassy. For these reasons the slags produced by smelting iron ores in the blast furnace have up until now proved most suitable for cement manufacture.

Other types of slags have high crystallization potential and cannot be obtained in the glassy state even under the high rates of cooling attainable in very efficient granulation plants. Into this category fall some of the slags produced in the electric arc smelting of ferro-alloys. In view of the conditions obtaining in the electric arc furnace and in the process features the slags are frequently tapped with a considerable superheat. The possibility therefore exists of changing the composition of the slags to increase the viscosity and thereby reduce the crystallization potential. It may be necessary to steer a very careful course between keeping the final chemical composition within the range giving a suitable modulus of composition of the type shown in page 218 of the paper and yet increasing the viscosity to a value which will reduce the crystalline potential to a level that will give a glassy material when the slag is granulated.

This in rough outline was the object of the test work described in our paper. The composition of one of the slags produced at the R.M.B. ferro-alloy plant appeared to be acceptable from the standpoint of chemical composition. Test work however, indicated that the solid slag contained much too great a proportion of

crystalline phase to be acceptable for cement manufacture. Acceleration of cooling rates to values considerably above those attainable in a granulation plant did not significantly reduce the proportion of crystalline material obtained. The only feasible alternative was therefore to increase the viscosity of the slag by making additions of silica.

As shown in Fig. 1 of the paper, the additions of silica had a marked effect in lowering the liquidus temperature of this particular slag composition. This has considerable practical significance in relation to the addition of substantial quantities of silica to the slag after tapping. Fig. 2 clearly indicates that as the rate of cooling is increased the pseudo liquidus temperature is lowered still further until when more than 10 per cent silica is added there is no detectable liquidus temperature and the slag consists of more than 90 per cent glass.

These findings are confirmed by the data in Table I of the paper which shows the percentage of glass formed under three different rates of cooling. From Table I and Fig. 3, it may therefore be concluded that when this particular slag composition is cooled at rates comparable with those attainable in an efficient granulation plant addition of 10 per cent by weight of silica yields a product with over 90 per cent glass.

Table II and Fig. 4 of the paper give the results obtained when calculating the Parker and Nurse Strength Index (I). This parameter is derived from the equation shown on page 219 of the paper and involves a combination of a chemical composition modulus and the glass content. Fig. 4 very clearly indicates quite a sharp maximum for the parameter I at a silica addition of 10 per cent at all the cooling rates employed.

Table III of the paper shows the compressive strength after 21 days of a Portland cement and a typical mixture of 2 parts Portland cement/1 part of slag, the values obtained being virtually identical. We conclude therefore that an index of the Parker and Nurse type, combining composition modulus and glass content, provides a reasonable basis for the rapid assessment of the effect of modifying the composition of the slag on the strength of the slag cement produced.

Contribution to discussion

Dr N. Stutterheim* (Visitor): In their preliminary considerations the authors deal with the generally accepted criteria whereby one can decide if a particular slag is suitable for use in cement. In this they refer *inter alia*, to the slag composition moduli that have been developed particularly in Europe, for predicting hydraulic performance. The current thinking about such moduli is that they are at best a rough guide to probable hydraulic behaviour rather than a dependable index. Evidence of this is the fact that there are a wide range of these moduli, and investigators still attempt to bring about modifications in them to accommodate new experimental evidence. Even so, there is still no general agreement about the most dependable modulus and many moduli have been materially modified, to explain the effects of components previously thought to be neutral or adverse. Examples of these are the introduction of the square of MnO in the denominator, and more recently the admission of magnesia to the numerator as, after all, it was found to play a role not unlike that of lime which, as Schröder pointed out in the recent Fifth Symposium on the Chemistry of Cement in Tokyo, is a revision of the older view that Mg^{2+} with fourfold co-ordination operates as a networkformer.

*Deputy President, S.A. Council for Scientific and Industrial Research.

Nevertheless, there is little doubt that if a wide range of compositions of slags were to be studied experimentally for composition, glass content and strength, even with other variables like fineness, accelerator or strength testing age controlled, not one of the current formulæ would provide an adequate expression for the relationship between composition and strength. The authors are aware of this and what use they have made of a modulus is, I think, justifiable because they have employed it for predicting the behaviour of one slag modified in composition over a very limited range. For such a purpose the use of a modulus such as that of Parker and Nurse as a first step is justified provided too great dependance is not placed on the indications.

The experimental technique employed by the authors, based mainly on the heating microscope, is one in which they have proved themselves particularly adept, not only for this study but also in other more extensive researches. The authors have taken into account that it is essential that slag intended for use as a cementitious material should be in the glassy state, since in contrast to Portland cement, crystalline components of slag do not contribute to strength development.

According to the authors, the slag as produced with the particular raw materials and processes concerned, is not of a suitable composition for cement manufacture, firstly because they anticipate that it will not yield a high glass content if granulated and secondly, because its chemical composition deviates too much from the region of optimum performance. The proposal to modify the composition by the addition of a cheap and readily available material like silica, is therefore a particularly interesting one and they demonstrate within the limitations of their experiment that this seems feasible.

In most metallurgical processes in which slag is involved, the latter is a means to an end, not an end in itself. Operators of slag-producing metallurgical processes are therefore understandably reluctant to do much about the slag's physical or chemical state once it has performed its metallurgical function. The authors have demonstrated that this slag has the potential to be converted from a waste product to an economic by-product.

Of particular interest is the fact firstly, that the slag as produced in this ferrochrome process has a high degree of superheat and secondly, that the composition modification by an addition of silica as proposed by them, will materially reduce the liquidus temperature. This is an intriguing finding, and one well worth following up on ladle scale in practice, in part to establish whether such addition will yield a sufficiently uniform batch of glassy granulate, but particularly to allow experimental cements in reasonable amounts to be made. It is unfortunate that the authors could not have reported such a practical test at works to confirm their predictions, but I presume this is a step that will follow: the authors might perhaps today give us some information.

I want to return for the moment to the question of glass formation during granulation. The authors mention that from studies, not detailed in this paper, they have concluded that the rate of cooling during full-scale commercial granulation is of the order of 50°C per second. My own assessment of the rate of cooling in commercial granulating plants (I have not measured this) is much higher, viz. in the region of 500°C per second; with a very efficient granulation plant it may be as high as 1,000°C per second. A practical indication of this is that in some granulation plants where high pressure water jets impinge on a stream of molten slag in a channel leading to a settling tank, the period from first impingement to final drowning of

the granulate is probably less than a second: in this period it is cooled to a state where little or no evidence of glow due to temperature remains. Depending on lighting conditions a dull red heat would be in the region of 500°C to 600°C; thus cooling of 1,500°C to 500°C in a second seems to be an achievable rate in practice, certainly for the bulk of the slag.

It may be worth while therefore for the authors to establish whether, from the point of view of glass formation, a lower addition of silica is not possible as that would give wider scope for achieving optimum addition of silica for strength development. There is another reason in favour of greater flexibility in this regard: the higher the initial slag temperature at time of granulation, the better its strength development, all other factors being the same. This indicates that although a slag may be well above its liquidus temperature, there are advantages in quenching it at as high a temperature as possible, quite apart from the ultimate glass content. Attempts to achieve optimum composition should therefore not be made at the expense of other favourable factors since ultimately a marginal advantage may be offset by a disadvantageous effect in another direction.

One interesting feature of slags is that the factors which determine their metallurgical performance, viz. temperature, viscosity and chemical composition, also determine the quality of the resultant granulate. Composition determines the glass-forming character, whether Frenkel type, Bernal type or Stewart type. Frenkel liquids are difficult to cool to glass; their structure bears no relationship to the configuration of the corresponding crystal phases. Their viscosities are low and the thermal coefficient is small. They are generally high in CaO and MgO. Bernal type liquids on the other hand have a structure related to that of the corresponding crystalline phases; they cool readily to glass. Stewart type slags tend to form threads or fibres when drawn out—they are generally high in SiO₂, too high for optimum hydraulicity.

Most slags are mixtures of these three types. The unmodified slag used by the authors is probably of the Frenkel type; addition of SiO₂ changes it to have more of the Bernal liquid characteristics.

Interest in utilizing industrial waste products like slags is apparently increasing throughout the world. During the Fifth International Symposium on the Chemistry of Cement held in Tokyo last October, a whole session was devoted to slags and cements made from them, with active participation from many countries.

Much work remains to be done to explain the behaviour of hydraulic glasses during hydration. Being amorphous materials, it is more difficult to establish their structures than in the case of Portland cements which are largely crystalline; moreover in the latter case one can identify the components and synthesize them to study behaviour and properties.

I take this opportunity to congratulate the authors on the work they have done, and to encourage them to continue with their researches.

B. van der Merwe* (Visitor): At the outset I would like to express my appreciation of this excellent paper. The authors have presented a very elegant method for the evaluation and comparison of slags that can be used in the manufacture of cement. No doubt the method could also be adopted to evaluate slags for related processes as well.

*R.M.B. Alloys (Pty.) Limited.

A fair amount of work has already been done on the use of the waste slag from the ferrochromium process in cement and cement mixes. The results of the majority of these tests were that there was inferior strength development after seven days, 28 days and three months and it was evident that certain modification of the slag was necessary to make it more suitable. The authors have now shown that there is definitely one method to achieve this modification and to assess its suitability even before manufacturing the cement.

The analysis supplied for the slag appears to be high in alumina. Recent calculations and analyses have shown alumina contents of 12 per cent compared to the 16 per cent quoted. A more typical analysis of the slag from the present process appears to be:

Component:	CaO	MgO	Al ₂ O ₃	SiO ₂	FeO	Cr ₂ O ₃
Percentage:	45.4	11.0	11.8	28.2	0.3	3.0

Using this analysis, at the 10 per cent silica addition level, gives a modulus of 1.37 and a Parker and Nurse index of 97. Since the index was taken to give an indication of the strength, and the actual strength was shown to be 98 per cent this appears to increase the usefulness of the index as a basis for prediction.

From the producer's point of view the most important question raised in this paper is the feasibility of adding 10 per cent silica to the slag before granulation. The liquidus temperature for 10 per cent silica addition is about 1,380°C, but to granulate at this temperature would not be practical, since there would be a danger of slag freezing on the walls of the ladle causing an intolerable build up. For this reason, I feel, the temperature of the material in the ladle after the addition of silica should not be below 1,450°C.

Based on the slag analysis shown above, the heat capacities of the various components were calculated at 1,450°C. Adding their appropriate contributions shows that there is 74,000 calories available from 900 grams of slag cooling from 1,750°C to 1,450°C and 100 grams of silica requires 48,000 calories to heat from 27°C and melt at 1,450°C. There is thus about 53 per cent of excess heat available and the addition of 10 per cent silica is feasible.

Furthermore, however, X-ray analysis of the granulated slag has indicated the presence of Merwenite, a di-calcium silicate and the spinels of alumina and chromium. A typical slag can then be calculated to contain:

Merwenite	36 per cent
Di-calcium silicate	43 per cent
Magnesium aluminate	17 per cent
Magnesium chromate	4 per cent

If these compounds exist in the molten slag, the heat available from 900 grams of slag cooling from 1,750°C to 1,450°C will be 79,000 calories. This gives an excess heat available to heat and melt 100 gm silica of 65 per cent.

It would therefore, appear that the addition of 10 per cent silica is possible provided that:

- (a) Care is exercised to obtain a sufficiently intimate contact between the silica and the slag to prevent localized freezing.
- (b) The slag temperature before the addition of silica is in the region of 1,750°C. As the process is worked at present the temperatures during granulation,

taken with an optical pyrometer, is in the region of 1,600°C to 1,620°C. At these temperatures it is very doubtful whether an addition of as much as 10 per cent silica is possible. This does not mean, however, that a modification to the process could not be made to give temperatures nearer 1,700°C to raise the heat content of the slag sufficiently to melt the required amount of silica.

As a point of interest I applied a variance ratio test to the standard deviations found for the strength of the mortar cylinders. This gave a value for $F = 3.68$ and is very close to the value for the 1 per cent level of significance (3.86). Since therefore, the standard deviations appear to differ significantly it is not strictly correct to accept and compare the average of the compressive strength. However, I have no doubt that this fact will resolve itself when more tests are done.

In conclusion, I would like to raise one more question although it is not really within the scope of this paper. Previous work has shown that the existing granulated slag was more difficult to grind than blast furnace slag. Would the same apply after the proposed modification or would the increased glass content improve comminution?

Finally, I would again like to take this opportunity to congratulate the authors on their very lucid and enjoyable paper.

Dr F. S. Fulton* (Visitor): I have read the paper presented by Professor Howat and his co-authors with keen interest, and must congratulate them on their classic approach to and solution of a complex research problem. Faced with the problem of slag utilization, they have considered the possibilities, discarded those which offered least promise, and by systematic test have established an optimum procedure for the study of the suitability of slag for cement manufacture.

I am interested too, in the difference between the authors' approach and that of the British Iron and Steel Research Association. The objectives of the latter organization was to produce from blast furnace or steelmaking slags a micro-crystalline material which by reason of its mouldability and high compressive and flexural strength would find useful application in the building industry. This they accomplished by adding silica to the slag, together with a small quantity of nucleating agent, and by devising a carefully controlled heat treatment for the melt.

In contrast the authors have aimed at producing a material having maximum glass content, this being achieved also by the addition of silica and by instituting a controlled cooling regime. The interesting point is that BISRA used 3 per cent of chromium oxide as one of the nucleating agents effective for the promotion of crystal growth. It is possible that the presence of roughly this amount of chromium (in whatever form it may be), in the slag described by the authors may prove troublesome in any plant scale operation. The matter is the more important as the generally accepted lower limit of glass content of South African slags used in cement manufacture is 95 per cent, although the figure of 85 per cent mentioned by the authors is commonly used in Europe. The amount of silica added also appears to have a critical effect on the Parker and Nurse modulus, and this points to the need for rather careful control of plant scale beneficiation.

*Portland Cement Institute

One point rather puzzles me. Because only limited quantities of material were available the authors used test specimens moulded into small cylinders as described by Professor Adolf Meyer. These were cured under water for 28 days, although Meyer's method requires steam curing for one hour at about 8 atmospheres. The mix proportions and the curing period actually used by the authors were therefore much the same as those specified for the standard mortar cube test used by the cement industry in South Africa; yet the strength achieved at 28 days was only about 2,650 lb/in.². An average South African cement containing 50 per cent of granulated slag would be expected to exceed this figure at 3 days, and reach about 8,500 lb/in.² at 28 days. The disparity could be due to differences in compactive effort and so on, but possibly in future work the use of the standard mortar cube would provide a more suitable yardstick than the small cylinder.

The matter is the more inexplicable as the modified slag used by the authors was ground to pass a 325 mesh sieve. In the Republic the standard method for measuring cement or slag fineness is by means of the Blaine permeability apparatus. Although there is no correlation between the two measures of fineness I would estimate that the slag used by the authors had a Blaine surface area exceeding 5,000 sq cm/gm. This would tend to exaggerate its pozzolanic properties, as the milled slag extensively used in slag/cement blends in South Africa is only ground to something over 3,500 Blaine. In portland blast furnace cement the slag is even coarser due to preferential grinding of the softer cement clinker.

This is one of the economic features which need close study, since in practice the cost of grinding slag rises very steeply for surface areas exceeding 4,000 Blaine. Another economic aspect which needs consideration is the desirability of using cement and slag in the proportions of 65 to 35. Obviously the higher the proportion of the cheaper ingredient the more economic would be the use of the final product.

I fully appreciate that the authors have reported on a pilot feasibility study, and once again congratulate them on the success they have achieved. My remarks should be regarded only as suggestions for carrying the investigation one step further.

Authors' Replies

Prof D. D. Howat (Author): May I say on behalf of my two co-authors that we are deeply grateful for these very fine contributions that have been made, and their critical appraisal of the work that we have done. It is very gratifying to know from Mr van der Merwe's calculations that at least the thing is feasible from a practical point of view. That was the very large unknown factor in the whole investigation—would it have any chance at all of being feasible on the plant, and Mr van der Merwe's calculations indicate fairly clearly that our hope may be realised.

With regard to Dr Stutterheim's query about further work, I am very glad to be able to say that through the courtesy and good offices of R.M.B. Alloys, we in fact hope to be able to carry this to the stage at which we can get sufficient quantities of material to render possible the type of tests that Dr Stutterheim was particularly anxious to have. We realised that this was needed and that the work would be incomplete and incapable of any analyses from an economic point of view without such data. I am glad to say that R.M.B. Alloys are prepared to give us these facilities to make these tests possible.

With regard to Dr Stutterheim's other point on the rate of cooling of the slag, I am sure Dr Jochens can offer some very useful comments on that point and I would like him to do so, and I think probably Mr Wolhuter could give Dr Fulton some further ideas about the conditions that governed his choice of the test conditions.

Dr P. R. Jochens (Author): I would like to answer one query that Dr Stutterheim made, and I must agree with him that the normal cooling rate on a granulation plant would be about 500°C per second. I had an opportunity to visit a plant in Scotland where they have managed to measure the rate and it is of the order of 500°C per second. Why then do we use 50°C per second? The point is that we managed to get hold of a lot of granulated material from various plants—this included Iscor, some places in Switzerland, and so on—and these particular slags were put on the micro-differential thermal analyser and cooled at various rates, until we managed to get the same amount of glass as had been obtained by treatment on the granulation plant itself. So this is actually a simulated granulation plant cooling rate, and this cooling rate happened to be 50°C per second. Why our cooling rate is perhaps so low, is that our particle size is also very much smaller than the normal particle size which forms on a granulation plant. I would estimate that the normal particle size on a granulation plant is of the order of two millimetres diameter, whereas ours in fact was only 0.2 mm. This is a factor of ten and, consequently these much smaller particles cool much more rapidly.

The other point that Dr Fulton made was whether we had considered producing slag ceramics from these particular slags. During a visit to the BISRA Laboratories in England, I found the investigators unhappy about the reception that slag ceramics had had in England. They have been working on it for the last six to eight years but nobody is yet producing slag ceramics in England. We have spent quite some time working on the slags produced at Highveld which, of course, contain a large proportion of titania which is an even better nucleating catalyst than vanadia but at present there would appear to be no market for slag ceramics in this country.

Mr C. W. Wolhuter (Author): Dr Fulton has suggested the answers to a number of the questions he has raised. The choice of the test method was determined by the fact that the quantities of material available were of the order of a gramme or two, and we wanted to adopt a form of test which, as far as possible, would be similar to the standard mortar tests in the proportions of the materials and the method of curing, but the standard mortar cubes have a dimension of something like seven centimeters which, of course, was quite outside our reach in this particular case. So we simply selected what we felt to be the best available method of making very small test specimens at this stage.

The very low strength we obtained is a matter that has caused us some concern about this test method, and as we mention in the paper, we feel that a considerable amount of further investigation would be required before this can be suitably standardized. The test procedure was to apply the load in a machine in which the load measurement was obtained from the reading on a proving ring. One can see from the standard deviations that the variability was such as to make the test at this stage not really acceptable as a standard procedure.

The choice of the slag-cement ratio, in this case 65 to 35, was simply to use in this preliminary pilot study an index which was already available, and on which we intend

to do more work to find an index which would be more suitable for South African conditions.

The choice of a 325 mesh sieve for grinding was rather arbitrary. We wanted to obtain material in a relatively reproducible fine state, and again the quantities were not such that we could adopt on an ordinary laboratory scale with this amount of material a process of grinding and repeat tests.

BOOK REVIEW

Non-Ferrous Extractive Metallurgy in the United Kingdom. Price £6.

This volume, which was advertised in the December, 1968, issue of the *Journal* at a pre-publication price of £4, is edited by W. Ryan of Warren Spring Laboratory and published by the Institute of Mining and Metallurgy, London. It is an up-to-date review of the operations of some 50 or so companies whose activities embrace the extraction and refinement of metals in the United Kingdom. Thirty-four metals are discussed, ranging from aluminium to zirconium and also there are chapters on ferro-alloys, non-ferrous alloys, high purity metals and metalloids, the platinum group metals and the rare earths. The sources of the various metals are given, followed generally by a brief description of the primary recovery process. Thereafter the operations of specific companies that deal in a particular metal are described in some detail. Certain metals such as barium, bismuth, gallium, thallium and zirconium are perforce covered very briefly as their commercial application is limited but in other cases, especially aluminium, copper lead and zinc, fairly detailed descriptions and illustrations are provided.

This publication should be of considerable value to students as it presents modern procedures with regard to the refining and uses of the particular metals under review. This information may not be available from text books which in any case tend towards obsolescence. The book should also prove a valuable addition to the bookshelves of practising metallurgists providing, as it does, a schedule of most of the metallurgical companies operating in the United Kingdom.

The quality of the paper and binding, the clarity of printing and illustrations and the arrangement of the subject matter are excellent and are subjects for which the editor and publishers are to be commended.

R.J.A.