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THOMAS RESEARCH SERVICES LTD.

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Report on

RESEARCH ON HUNGARIAN STEELWORKS SLAGS

A PRIMARY INVESTIGATION OF COMPOSITION & PROPERTIES

for

THE RESEARCH LABORATORY FOR INORGANIC CHEMISTRY
THE HUNGARIAN ACADEMY OF SCIENCES

and

THE UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANISATION

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SUMMARY

A total of ten samples of steel slags from three different Hungarian steel works have been analysed and tested to assess their potential for utilisation.

The basic mineralogy of the samples have been established and their physical properties and volumetric stability characteristics studied.

Overall the results indicate a mineralogy generally characteristic of air cooled basic steel slags but with some apparently distinctive differences in minor phases present.

When judged against most road aggregate materials available, the tests for physical strength showed the slags generally to be very strong. However, there are serious potential volumetric stability problems.

It is judged that the slags may be utilisable if a processing regime can be established to permit the marketing of these slags into specific applications.

Recommendations for further work aimed at establishing processing routes for specific markets are included.

RESEARCH ON HUNGARIAN STEELWORKS SLAGS

A PRIMARY INVESTIGATION OF COMPOSITION AND PROPERTIES

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RESEARCH ON HUNGARIAN STEELWORKS SLAGS

A PRIMARY INVESTIGATION OF COMPOSITION AND PROPERTIES

1. INTRODUCTION

Research is necessary in order to establish the basic characteristics of Hungarian steel slag to facilitate plans for their future commercial utilisation.

The main objectives of the programme are:

a) To identify the chemical and mineralogical composition of the main Siemens Martin, L.D. and electric furnace slags produced by the Hungarian Steel Industry.

b) To list known mechanisms likely to give rise to volumetric instability problems and to propose, where practicable, possible solutions.

c) To carry out an initial assessment of any potential volumetric instability employing both "real time" and "accelerated" expansion tests.

d) On the basis of the above tests, to advise on the scope for utilising Hungarian steelworks slags.

To facilitate this research, ten steelworks slag samples were selected from three Hungarian works:-

At Danube Ironworks, Ferromark Ltd, three samples of mixtures of L.D. and S.M. slag were taken. One sample was "fresh-make", one was from slag 4-5 months old, and the last was chosen from a slag several years old.

Three slag samples were taken at Dimag Ltd, Diosgyor. Two slags were from the L.D. process; one "fresh-make" and one "old". The third slag sample was from the electric arc process and was "fresh make".

Sampling at Meteor Ltd, Ozd, was all of S.M. slag. Four samples in all were chosen:

One sample of fresh-make slag.

One sample of old S.M. slag transported from the slag tip into the plant.

One sample of old S.M. slag from the tip.

One sample of old S.M. slag taken from the tip after magnetic separation.

Most samples were between 35 - 40 kg in weight. All the slags were transported to the T.R.S. laboratory in Barton-on-Humber, U.K., for processing, testing and analysis.

2. LABORATORY PROGRAMME

On arrival at the laboratory the samples were first visually examined. As they consisted of large pieces of slag they were then reduced in size by a first pass through a large laboratory jaw crusher. Each sample was then quartered, and the resulting representative samples "low - temperature dried" prior to stage-crushing, quartering again, and milling to produce the finely divided material required for chemical and thermal analysis.

The following programme of analysis and testing was then carried out.

2.1 Phase content by X-ray diffraction.

2.2 Optical microscopy on six of the ten samples received. These samples were chosen to include material from each of the three works, and the different categories of slag sampled.

2.3 Thermal analysis was carried out on all samples, as was chemical analysis for free lime and free magnesia.

2.4 The volumetric stability of all samples was assessed using the Thomas Research Services Ltd accelerated expansion test.

2.5 The magnetic content of the ten slags was determined.

2.6 The as received moisture content and water absorption properties of the samples were determined.

2.7 The samples were subjected to the "iron unsoundness" test of British Standard 1047.

2.8 The aggregate impact and 10% fines value tests were carried out.

2.9 Samples were submitted for the polished stone value test.

Items 2.6, 2.8 and 2.9 were all carried out in accordance with the appropriate clauses of British Standard No. 812.

3. RESULTS

3.1 The X-ray diffraction results are given in table 1 which shows the 21 phases identified and their relative amounts using a scale in which 1 indicates a predominant phase, (say over 90%), and 7 is a trace amount.

It must be emphasised that the XRD techniques employed do not yield precise quantitative values. Only a very approximate indication of quantity is obtained. However, the data does provide some indication of relative concentration.

3.2 The observations made in the petrological examination of the samples are detailed in appendix A and summarised in table 2. Fourteen minerals/phases were identified.

3.3 Table 3 gives the results arising from differential thermal analyses and thermogravimetric analyses. It should be noted that although specific values are recorded, the test is only semi-quantitative. Also included in this table are the chemical analysis results.

The values % residual free lime and residual free magnesia are arrived at by adjusting the original results for any $Ca(OH)_2$ and $Mg(OH)_2$ present. Free CaO and free MgO analyses arrived at by traditional wet chemical analysis techniques include the CaO and MgO attributable to any hydrated material which may be present. As it is the hydration reaction which can give rise to volumetric expansion, it is important to recognise the residual figure as the value likely to represent any future expansion potential. The hydrate figures used in the calculations are

listed in table 3. Where no hydrate is present, or only "trace" is recorded, then clearly the "residual" or available free CaO or free MgO is unaltered.

3.4 Table 4 records the daily measurements made during the T.R.S. accelerated expansion test. The test procedure has been developed to forecast potential future expansion. This test is normally complete after 14 days. However, when steel slags are being evaluated it is often necessary to extend the duration of the test.

Reference to table 4 shows that measurements continued up until day 29. The results listed are per cent expansion. (see Fig 7 & 8.)

3.5 Reference to table 5 shows the magnetic content of the 10 slags tested to range from 0.87% to 38.71% with a mean of 8.99%.

3.6 As would be expected the as received moisture, and water absorption properties are both low. Values are given in table 5. The

as received moisture content ranges between nil and 1.05%, with a mean of 0.29%. Water absorption determined in accordance with BS812 varies between 0.50% and 5.44% with a mean of 1.91%.

3.7 Table 5 gives the results of the "iron unsoundness" test carried out in accordance with BS1047. Sample LD-2 failed the test as one piece of the immersed sample disintegrated during the 14 day test period.

3.8 Table 5 gives aggregate impact values (A.I.V.) determined in accordance with BS812, and 10% fines values determined in accordance with the same British Standard. Aggregate impact values range between 14 and 42 with a mean of 25. 10% fines results range between 47 kN and 279 kN with a mean of 154 kN.

Improving properties are indicated by high values in the 10 per cent fines test and lower values in the aggregate impact test.

There is an empirical relationship between aggregate impact value, and 10% fines determinations whereby:-

$$\frac{4000}{A.I.V.} = \text{approximate to 10\% fines value}$$

With the exception of LD-2, which gave a particularly low 10% fines value the other samples gave results which approximately comply with the above relationship.

The polished stone values included in table 5 have been carried out in accordance with BS812, part 114. The test procedure simulates the effect of a standard amount of traffic on a sample of the slag roadstone. The effect of this trafficing is then measured using a pendulum type device.

High results are judged to indicate superior polished stone values.

4. DISCUSSION OF RESULTS

4.1 MINERALOGY

Crystalline blast furnace slags and basic steel slags have distinctively different mineral compositions. The mineral content of most air-cooled blast furnace slags is commonly dominated by melilite, a solid solution of which the two end members are gehlenite ($2CaO.Al_2O_3.SiO_2$) and akermanite ($2CaO.MgO.2SiO_2$).

In many crystalline blast furnace slags melilite may represent 90 per cent or more of the products composition. Other phases present commonly constitute only minor components of the total content.

Basic steel slags have distinctly different mineralogies. Commonly no single phase forms such as high a proportion of the mineral content as melilite in blast furnace slags. Generally the mineralogy is much more varied and the proportion of phases present can vary significantly even in slags from the same furnace.

L.D. slags often have five mineral phases present:-

Alite - $3CaO,SiO_2$

Larnite - $\beta 2CaO.SiO_2$

An RO phase of the wustite type which may include CaO, MgO, MnO and Fe a "ferrite" solid solution phase with possible end members C_4AF and C_2F "Free" CaO (and for possibly "free" MgO).

Alite is frequently absent and when present frequently shows evidence of breakdown into larnite and free lime.

In many L.D. slags, larnite is the most abundant phase, but does not dominate the slag composition.

The R.O. wustite type phase and the ferrites are usually present, commonly as interstitial components.

Basic steel slags invariably have some free lime present. In L.D. slags this can sometimes be high. Most free lime is the

uncombined residue of lime added during the steelmaking process. Small quantities can sometimes be derived from the breakdown of alite - as already indicated. There is some evidence - as yet inconclusive, that occasionally free lime can be reprecipitated from the slag melt.

Siemens Martin slags and slags from the electric arc furnace, tend to have even more variable compositions which can result in a still more diverse mineral composition.

In the slags being studied the diversity has been increased still further by the common tipping of differing slag types at Danube Works.

4.1.1 X-RAY DIFFRACTION RESULTS

The results of work on slags from all three sites are summarised in table 1. Some distinctive differences are immediately apparent namely:-

a) Slags from Danube and Meteor works all have dicalcium silicate present. In most instances it is the beta form (Larnite)

although in one instance it occurs as Bredegite i.e. alpha C_2S.

b) Slags from Dimag have no C_2S but alite (C_3S) is present together with, in one sample surprisingly, gamma C_2S. The presence of alite rather than dicalcium silicate may be an indication of high lime values in the slag.

c) An RO solid solution of the wustite type is present in all samples. In all but one sample the phase appears to be magnesia rich. In the exception lime appears to dominate the composition.

d) Ferrite solid solution phases are present in all samples except SM3 (X986).

e) No free lime has been identified by X-ray diffraction, although this is common and should not be taken to indicate its absence. Periclase was found in one sample (X980 - DV-LD+SM2).

f) A melilite type phase was identified in 8 out of 10 samples examined. As will become evident from the microscopic examinations, some of this phase appears to be attributed to blast furnace slag mixed with the steel slag in old stockpiled material. However, there is some evidence of melilite in the interstitial material in some of the steel slags. The latter is a most unusual feature.

4.1.2 Petrology Results

Table 2 gives a summary of the minerals identified in the six samples examined.

The slags from the Dimag works are shown to be lime-rich, and are characterised by the presence of C_3S (alite) a phase known to breakdown into beta C_2S and free lime. Slag samples from Danube and Meteor Ltd on the other hand are more siliceous being characterised by C_2S and various silicate phases. The identification of these silicates, often present in quite small amounts can be difficult. X-ray and petrological results can be at variance to some extent. Cuspidine, found in samples X980 (DV-LD+SM3) and X986

(SM-3) and Nagelschmidite identified in X983 (UHP-1) were not identified by X-ray diffraction.

An unusual feature of these slags is the occurrence of melilite. Melilite identified petrologically is confined to the more siliceous slags X980 (DV+LD-SM3), X984 (SM-1) and X986 (SM-3). Melilite, which X-ray data identifies as being of akermanite type ($2CaO.MgO.2SiO_2$) is found as an interstitial phase representing a late-cooling stage relatively siliceous liquid. However in contrast to the optical petrology results X-ray diffraction also indicates a more lime rich melilite closer to gehlenite (C_2AS) in the lime rich slags from Dimag Ltd.

4.2 THERMAL ANALYSES AND CHEMICAL ANALYSES

The evidence produced by thermal analysis relates largely to changes which occur in the slags after cooling, e.g. the effect of weathering.

It is immediately apparent that no ettringite has formed and that no gypsum is present (other than traces in SM-3A, X987). Clearly

this is due to the slag being of basic steel rather than blast furnace slag origin.

Normally only blast furnace slag has a significant sulphur content which can oxidise on weathering to give rise to gypsum. Ettringite is the product formed in some weathered blast furnace slags where gypsum is present. The reaction is highly expansive.

The "trace" of both gypsum and ettringite in samples SM-3A (X987) from Meteor Works is presumable attributable to the presence of small quantities of blast furnace slag.

Calcite is a product of weathering. It is instructive to note that calcite, and other weathering products $Ca(OH)_2$ and $Mg(OH)_2$ can be present in "fresh make" steel slags. Some free lime and occasionally free MgO (periclase) can hydrate and carbonate quickly.

The free CaO and free MgO analyses are carried out by traditional wet chemical techniques and the values include the CaO and MgO equivalents of the $Ca(OH)_2$ and $Mg(OH)_2$ present.

The "residual" values recorded have been corrected for this component and now represent only the anhydrous free CaO and free MgO present.

Both analyses for free CaO and free Mgo include values at levels capable of giving serious problems of volumetric instability, if employed for unappropriate applications and by unsuitable production routes.

4.3 VOLUMETRIC STABILITY

The T.R.S. accelerated expansion test has been developed specifically with blast furnace slag and basic steel slags in mind. Differing treatment regimes are employed for different slag types and compositions. The accelerated test is intended to forecast potential volumetric instability that may occur over periods of several years.

The procedure has been correlated with "real time" expansion tests.

Results of stability testing using the TRS accelerated expansion test are given in table 4.

The samples from Dimag Ltd form a distinct group characterised by extremely high expansions, in the case of X982 (LD-2) 56.41%.

The samples from Danube Iron Works and Meteor Ltd also showed high expansions with only two samples X980 (DV-LD+SM3) and X987 (SM-3A) showing low expansion test results at the end of the 14 day period. However, the former sample continued expanding in the period 14 - 29 days and showed an expansion of 0.55% at the end of this period. X987 (SM-3A) did remain stable throughout the whole test period. This was the only sample of the ten tested to remain volumetrically stable.

As judged by the samples examined the tests clearly demonstrate that steel slags from these Hungarian steelworks are unlikely to remain stable in use unless subjected to a specific treatment regime and marketed on a selective basis.

Further research and development work would clearly be required to achieve these objectives.

4.4 PHYSICAL TESTS

The results indicated that the slags tested were strong with good 10% fines test values which would meet the BS1047 standard of a minimum value of 50. Aggregate impact testing offers a rapid method of monitoring their strength.

Polished stone values are generally within the range expected in air booled basic steel slags. However detailed comment on this property, which has a significant effect on "skid resistance" on roads, must await results on significant quantities of processed slag.

Water absorption values are low and the slags may be suitable for use in road construction, as a wearing-course. However, the high densities may result in low covering capacities.

5. CONCLUSIONS

The work on the ten samples of steel slag from the three works must represent only an initial assessment of the Hungarian steel slag available for utilisation. However, judged by the information generated by the research to date, some tentative conclusions can be drawn:-

a) In terms of mineral content, the slags exhibited some similarities to other steel slags examined by T.R.S. Beta dicalcium silicate , wustite, RO type solid solution and ferrites were common constituents. Alite was also present in some samples.

b) The likely presence of melilite in the interstitial material is most unusual, is unexpected and has not been encountered before.

c) Free CaO and free MgO are present in levels likely to cause volumetric instability problems unless appropriate treatment regimes and suitable market products are developed.

The accelerated expansion test confirm the liability to volumetric instability.

d) Physcial tests - almost all the slags gave excellent values. The slags have high mechanical strength and provided the volumetric stability problem can be overcome, should give first class in-use properties.

The high densities, which of course relate to the excellent strength properties, are likely to be a disadvantage in terms of "covering capacity".

It must be recognised that only a very limited programme on slags from these works has been carried out so the findings must, at this stage, be regarded as tentative.

6. RECOMMENDATIONS

a) Further work is required to evaluate in more detail the mineralogy and chemistry of the Hungarian slags.

b) "Weathering trials" to modify the volumetric instability properties need to be carried out. Detailed monitoring will be required in this work.

c) Subject to satisfactory completion of (b) practical but formally designed road trials should be carried out.

d) Work should be put in hand to evaluate the very large stockpiles of slag and to seek commerical exploitation.

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29th January 1991.

WORKS		DANUBE IRON WORKS			DIMAG LTD			METEOR LTD			
WORKS REF. / LAB. REF.		DV-LD+SM1 X978	DV-LD+SM2 X979	DV-LD+SM3 X980	LD-1 X981	LD-2 X982	UHP-1 X983	SM-1 X984	SM-2 X985	SM-3 X986	SM-3A X987
COL NO.	PHASE										
1	Melilite	6	-	6	7	5	-	5	5	4	4
2	Quartz	6	7	6	-	-	-	-	-	7	7
3	Calcite	-	-	-	5	6	-	-	-	7	-
4	Bredegite	-	-	-	-	-	-	-	6	-	-
5	Larnite	5	4	5	-	-	-	6	-	5	5
6	γ C_2S	-	-	-	6	-	-	-	-	-	-
7	Alite C_3S	-	-	-	4	4	4	-	-	-	-
8	CaOFeO	-	-	-	5	4	5	-	-	-	-
9	RO (FeO+CaOinss)	-	-	-	4	-	-	-	-	-	-
10	RO (FeO+MgOinss)	4	4	4	-	4	4	4	4	4	4
11	MgO	-	-	7	-	-	-	-	-	-	6
12	R_3O_4	6	-	7	-	-	-	5	7	-	-

TABLE 1 - SUMMARY OF X-RAY DIFFRACTION RESULTS

WORKS		DANUBE IRON WORKS			DIMAG LTD			METEOR LTD			
WORKS REF.		DV-LD+SM1	DV-LD+SM2	DV-LD+SM3	LD-1	LD-2	UHP-1	SM-1	SM-2	SM-3	SM-3A
LAB. REF.		X978	X979	X980	X981	X982	X983	X984	X985	X986	X987
COL NO.	PHASE										
13	Brown-millerite C_4AF/C_2F	5	5	5	6	6	6	5	6	-	5
14	$12CaO.7Al_2O_3$	6	6	7	7	-	7	7	-	-	-
15	Monticellite $3CaO.MgO.SiO_2$	-	-	-	-	-	-	-	5	5	-
16	Merwinite $3CaO.MgO2SiO_2$	6	-	-	-	-	-	-	-	-	-
17	T-Phase $5CaO.MgO.3SiO_2$	-	-	-	-	-	-	5	-	-	-
18	Mullite $Al_2O_3.2SiO_2$	-	7	6	7	-	-	-	-	7	7
19	Cristobalite	-	-	7	-	-	-	-	-	-	-
20	Tridymite	-	-	7	-	-	-	-	-	-	-
21	α- Fe	-	-	-	-	-	-	-	-	7	-

TABLE 1 (1 continued)

N.B. - The numbers shown demonstrate a very approximate, semi-quantitative indication of the relative amounts of each phase present. 1 indicates a predominant phase, say over 90%. The remaining numbers indicate decreasing quantities down to 7 which is a trace.

	Metal	Cus.	Ng.	Mo.	Me.	C_2S	C_3S	Roc	Pe.	Sp.	Li	Rf	Flu	Rust
980 A	s	l	-	-	s	s	-	l	s	s	-	-	-	-
B	s	-	-	-	-	l(b)	-	l	s	-	s/m	s	-	-
981	s/m	-	-	-	-	m	m/l	l	s	-	s/m	m	-	-
982	s	-	-	-	-	m(b)	m/l	l	-	-	s/m	m	-	-
983	s/m	-	s	-	-	m	m/l	l	-	s	s/m	m	s	-
984	s	-	-	m	s	m	-	l	s	s	s	s	-	-
986 A	s/m	m/l	-	-	-	-	-	l	-	s	-	-	s	s
B	s	-	-	m	s	m(b)	-	l	s	-	s	s	-	-

Cus. Cuspidine, Ng. Nagelschmidtite, Mo. Monticellite, Me Melilite, C_2S dicalcium silicate b indicates beta form, C_3S tricalcium silicate, ROc magnesiowustite complex including R_3O_4, Pe Periclase, Sp. Spinel, Li Free Lime, RF Dicalcium ferrite/brown millerite complex, Flu, Fluorite.

l is large, m medium and s small amounts.

TABLE 2 - SUMMARY OF STEEL SLAG MINERALOGY FROM OPTICAL PETROGRAPHY

WORKS	DANUBE IRON WORKS			DIMAG LTD				METEOR LTD		
WORKS REF. LAB. REF.	DV-LD+SM1 X978	DV-LD+SM2 X979	DV-LD+SM3 X980	LD-1 X981	LD-2 X982	UHP-1 X983	SM-1 X984	SM-2 X985	SM-3 X986	SM-3A X987
Loss on Ignition (%)	0.59	0.24	0.83	0.57	0.53	0.39	0.17	0.52	0.66	0.55
% Ettringite	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	tr.
% Gypsum	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	tr.
% Calcite	0.30	tr.	1.09	0.14	tr.	0.18	tr.	0.48	0.75	0.32
% $Ca(OH)_2$	0.42	<0.03	<0.03	0.69	1.90	0.99	<0.03	0.35	<0.03	<0.03
% $Mg(OH)_2$	0.13	<0.03	0.20	Nil	Nil	Nil	<0.03	0.14	<0.03	tr.
% Free CaO	1.40	0.34	0.28	8.86	7.74	8.64	0.39	0.79	0.73	0.50
% Free MgO	1.20	Nil	4.13	1.28	0.80	1.84	1.70	3.33	2.89	1.96
% Residual Free CaO	1.08	0.32	0.26	8.34	6.30	7.89	0.37	0.53	0.71	0.48
% Residual Free MgO	1.11	Nil	3.99	1.28	0.80	1.84	1.68	3.23	2.87	1.96

TABLE 3 - CHEMICAL AND THERMAL ANALYSIS RESULTS

WORKS	DANUBE IRON WORKS			DIMAG LTD			METEOR LTD			
WORKS REF.	DV-LD+SM1	DV-LD+SM2	DV-LD+SM3	LD-1	LD-2	UHP-1	SM-1	SM-2	SM-3	SM-3A
LAB. REF.	X978	X979	X980	X981	X982	X983	X984	X985	X986	X987
DAYS TREATMENT										
1	1.97	0.53	0.06	3.61	47.00	12.82	0.82	0.57	0.45	0.08
2	2.25	0.60	0.09	5.03	51.28	12.82	1.09	0.85	0.47	0.10
3	2.31	0.65	0.11	5.60	55.56	12.82	1.26	0.92	0.49	0.12
4	2.33	0.71	0.12	5.20	55.50	13.09	1.56	0.94	0.48	0.12
5	2.38	0.76	0.13	6.36	55.51	13.39	1.92	0.96	0.49	0.12
6	2.41	0.81	0.14	6.93	55.60	13.82	2.18	0.97	0.48	0.12
7	2.46	0.90	0.15	7.46	55.57	14.02	2.43	0.97	0.49	0.13
8	2.47	0.91	0.15	8.55	54.70	14.53	2.67	0.97	0.49	0.13
9	2.47	0.91	0.17	8.55	55.56	14.53	2.87	0.97	0.49	0.12
10	2.47	0.91	0.18	8.55	55.56	14.53	2.91	1.00	0.49	0.14
11	2.49	0.92	0.19	8.55	55.57	14.91	2.95	1.01	0.49	0.14
12	2.51	0.92	0.21	8.56	55.55	15.17	2.96	1.00	0.50	0.14
13	2.54	0.93	0.22	8.55	55.56	16.24	3.00	1.03	0.51	0.15
14	2.52	0.92	0.22	8.55	55.56	16.24	2.96	1.03	0.50	0.14

TABLE 4 - DETAILS OF ACCELERATED EXPANSION TEST RESULTS

WORKS	DANUBE IRON WORKS			DIMAG LTD			METEOR LTD			
WORKS REP.	DV-LD+SM1	DV-LD+SM2	DV-LD+SM3	LD-1	LD-2	UHP-1	SM-1	SM-2	SM-3	SM-3A
LAB. REP.	X978	X979	X980	X981	X982	X983	X984	X985	X986	X987
DAYS TREATMENT										
15	2.52	0.92	0.24	8.55	55.56	16.24	2.99	1.05	0.50	0.14
16	2.52	0.95	0.26	8.55	55.56	16.24	2.99	1.07	0.51	0.14
17	2.53	0.95	0.28	8.55	56.41	16.24	2.97	1.10	0.53	0.13
18	2.53	0.94	0.30	8.85	56.41	16.24	2.97	1.12	0.53	0.14
19	2.54	0.92	0.32	9.15	56.41	16.24	2.98	1.14	0.53	0.14
20	2.54	0.91	0.32	9.40	56.41	16.24	2.98	1.18	0.54	0.14
21	2.54	0.94	0.32	9.40	56.41	16.24	3.03	1.19	0.52	0.15
22	2.59	0.93	0.38	9.40	56.41	15.38	3.05	1.26	0.54	0.15
23	2.59	0.93	0.39	9.40	56.41	15.38	3.05	1.29	0.55	0.14
24	2.60	0.93	0.44	9.40	56.41	15.38	3.01	1.35	0.55	0.14
25	2.60	0.92	0.46	9.40	56.41	15.38	3.02	1.40	0.52	0.14
26	2.60	0.92	0.48	9.40	56.41	15.38	3.02	1.45	0.52	0.15
27	2.59	0.92	0.50	9.40	56.41	15.38	3.03	1.50	0.52	0.15
28	2.61	0.95	0.55	9.40	56.41	15.38	3.03	1.53	0.52	0.15
29	2.63	0.95	0.55	9.40	56.41	15.38	3.02	1.59	0.52	0.15

TABLE 4 (continued 1)

WORKS	DANUBE IRON WORKS			DIMAG LTD			METEOR LTD					
WORKS REF. / LAB. REF.	DV-LD+SM1 X978	DV-LD+SM2 X979	DV-LD+SM3 X980	LD-1 X981	LD-2 X982	UHP-1 X983	SM-1 X984	SM-2 X985	SM-3 X986	SM-3A X987	Range	Mean
% Magnetic Content	7.38	0.87	8.40	3.03	4.23	3.92	38.71	9.45	8.68	5.21	0.87-38.71	8.99
As Received Moisture Content (%)	0.15	0.36	0.41	0.06	0.10	0.05	nil	1.05	0.42	0.53	nil-1.05	0.29
Aggregate Impact value to BS812	18	14	27	19	42	29	23	22	30	26	14-42	25
10% Fines value (kN) to BS812	220	279	115	214	47	118	153	158	117	116	47-279	154
Iron Unsoundness to BS1047	pass	pass	pass	pass	fail*	pass	pass	pass	pass	pass	-	-
Water Absorption (%) to BS812	1.15	0.50	1.78	0.80	2.58	0.90	1.77	1.65	2.50	5.44	0.5-5.44	1.91
Polished Stone Value to BS812	63	63	61	60	62	57	66	64	60	61	57-66	62

Note:
* (one piece disintegrated)

TABLE 5 - PHYSICAL TESTING RESULTS

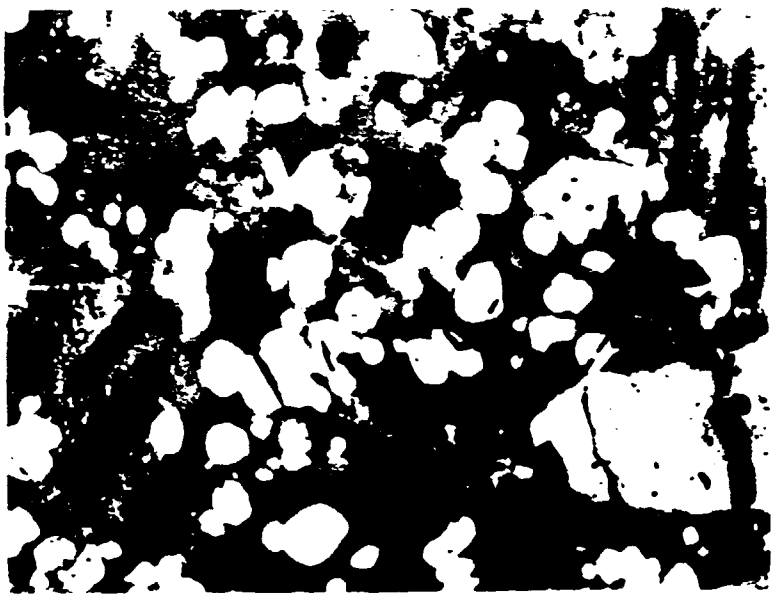

Fig. 1 X980 Steel slag consisting mainly of prismatic columnar cuspidine and RO phase with interstitial phases including melilite. Magnification X75

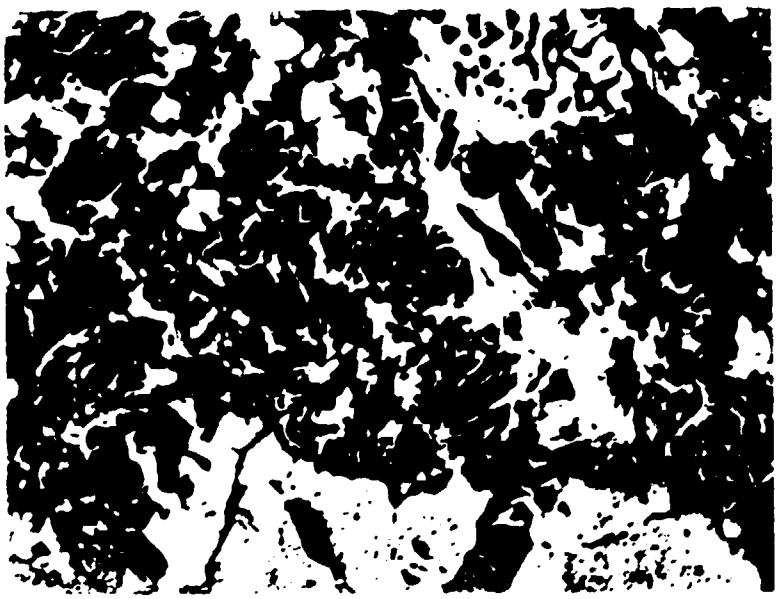

Fig. 2 X980 Steel slag formed mainly of RO and beta dicalcium silicate with subsidiary free lime (L). The RO phase is graditional in composition to residual periclase (P). Magnification X75

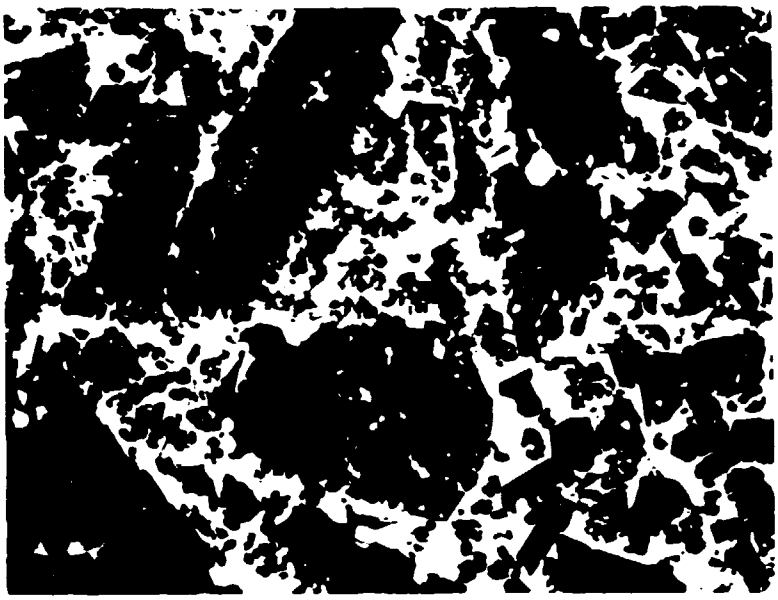

Fig. 3 X981 Steel slag consisting of prismatic crystals of tricalcium silicate in a matrix of dicalcium silicate, RO and R ferrite. The tricalcium silicate is in part converted to dicalcium silicate and free lime. Magnification X75

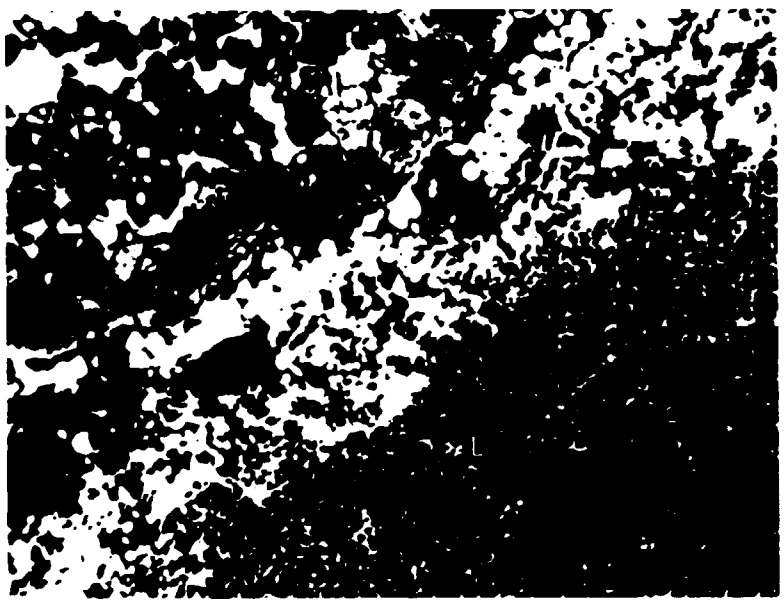

Fig. 4 X984 Steel slag consisting of nodular free lime (L) marginal by RO phase and dicalcium silicate. Magnification X180

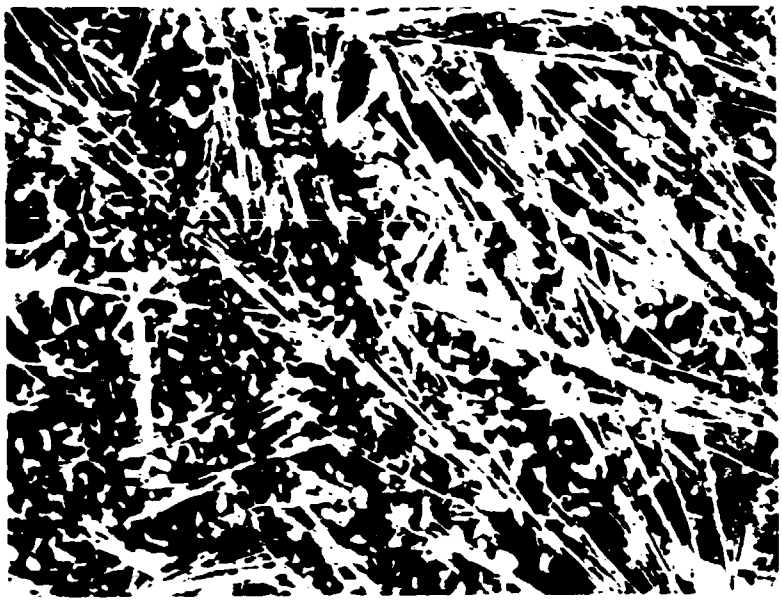

Fig. 5 X983 Steel slag consisting of finely granular RO, needle-like R ferrite with a matrix of tri- and dicalcium silicate. Magnification X75

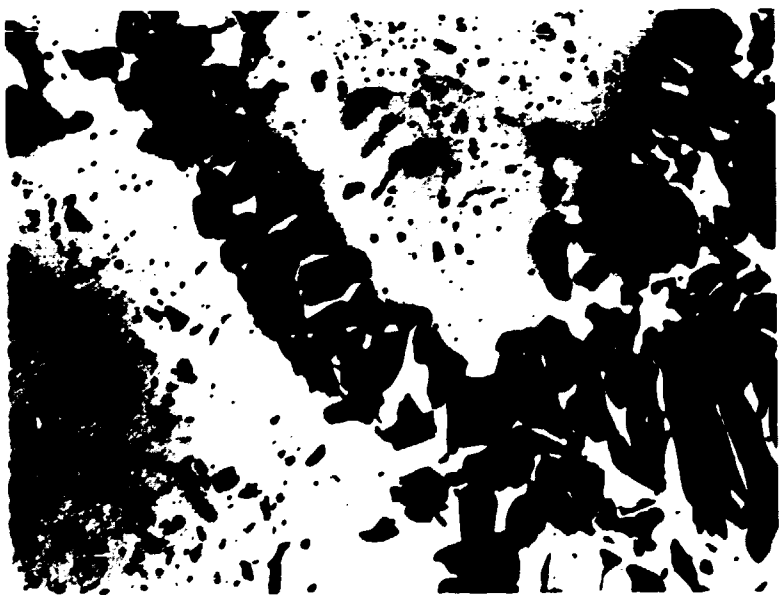

Fig. 6 X984 Steel slag consisting mainly of residual periclase (magnesite brick) with dicalcium silicate present along microcracks. Magnification X180

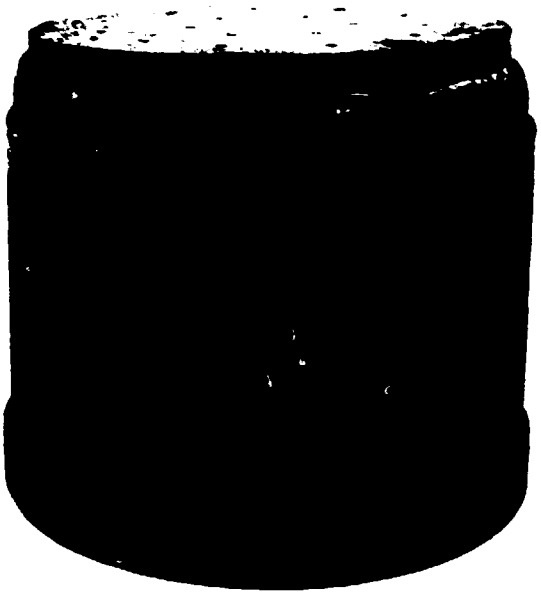

FIG 7 - SAMPLE X983

FIG 8 - SAMPLE X982

Slag samples after treatment in the T.R.S. Accelerated Expansion Test.

APPENDIX A

MINERALOGICAL EXAMINATION OF SAMPLES X980-X984 & X986

About 10 to 12 lumps were received for each sample. All were examined in hand specimen, small pieces cut off, dried, mounted polished and etched for microscopic evaluation.

Results are as follows:

X980

Steel slag (8 pieces), fresh, dark grey and mostly dense. There are two types A and B. A (the majority) consists mainly of an unetched silicate phase (UES) often with a well developed columnar (spinifex) crystalline texture (Fig. 1) together with RO phase (where R is mainly Fe with some Mg, Mn, Ca, etc.). Dicalcium silicate (small amount) occurs inside the UES crystals and a third silicate phase, probably melilite, interstitially to the UES. The optical properties, especially the multiple twinning, suggest the main phase is cuspidine ($Ca_4Si_2O_7F_2$). Spinel is present in small quantity and there are minor sulphides. The RO phase grades in composition locally to periclase. There are a few metal prills. Slag B consists mainly of beta-dicalcium silicate and RO phase and also contains some R ferrite phase (where R is mainly Ca) and free lime. Relict particles of periclase are marginally reacted to the RO phase (Fig 2). Also, the RO phase is complex in nature as a result of

reformation on cooling according to the reation:

$$R_XO = R_3O_4 + R_yO$$

Alumino-silicate brick (3 pieces). One is buff and two dark mauve-grey. Major components are quartz, mullite and glass.

Magnesite brick. This is dark reddish and consists of granular periclase with much finely granular exsolved hematite and magnesioferrite.

X981

Steel slag (14 pieces) fresh, dark grey and mainly dense. Metal common as prills. There is much textural variation but probably only one general type of slag is present. The main phases are RO phase, grading in composition to periclase, tricalcium silicate, dicalcium silicate, R ferrite and free lime. Most of the free lime is associated with the dicalcium silicate and probably results from decomposition of tricalcium silicate. Two pieces of slag contain substantial quantities of free lime in globular form (Fig. 3).

X982

Steel slag (10 pieces), fresh, dark grey, dense with occasional metal prills. Most consists of tricalcium silicate, dicalcium silicate (in part beta), RO phase, and R ferrite phase with some free lime. The typical crystal form

of primary tricalcium silicate is illustrated in Fig 4, with partial reformation as dicalcium silicate and lime. One piece of slag has a substantial amount of globular free lime. There is much textural variation, with changing local contents of the various phases.

X983

Steel slag (12 pieces), fresh dark grey, dense. Common metal prills. Most consists of RO phase, R ferrite phase (often needle shaped, Fig 5 and some forming platelets in pores visible to the naked eye), tricalcium silicate, dicalcium silicate and an unetched silicate phase probably nagelschmidite, a phase possibly spinel and small amounts of free lime. Fluorite noticed in one or two pieces and three or four pieces have coarse globular free lime.

X984

Steel slag (11 pieces), fresh, dark grey, dense with occasional metal prills and nuggets of free lime and periclase (Fig.6). There is much textural and compositional variation and there could be more than one type of slag present. Most consists mainly of a complex RO phase (R_xO, R_yO, R_3O_4), much near to periclase in composition, and unetched silicate phases (possibly nagelschmidite) and dicalcium silicate. There is minor R ferrite phase and some pieces contain spinel. Some melilite is present interstitially to the main silicates in some pieces. One

piece has relatively coarse aggregates of periclase, but free lime is mostly uncommon. One piece consists of Fe-rich RO phase, spinel and an unetched silicate, probably an R SiO type phase. This piece is considered to be so siliceous in composition that it represents a distinct slag type.

X986

Steel slag (9 pieces), slightly altered with pores infilled by spherules of a white mineral. Metal common, some with oxide scale and rust. Two types of steel slag are present, A and B. A consists mainly of an unetched silicate, possibly cuspidine, with RO phase and minor spinel, a seccnd (low refractive index) silicate, sulphides and fluorite. The RO phase is complex in nature and locally grades to periclase which is encapsulated. Slag B consists of RO phase, an unetched silicate phase, possibly monticellite, R ferrite phase, dicalcium silicate and interstitial melilite. Some RO phase is again near to periclase in composition but very little free lime seen. Some pieces are more calcic, with high dicalcium silicate contents including much in the beta form.

Blast furnace slag (3 pieces). Two are of crystalline blast furnace slag and consist mainly of melilite with minor oldhamite and beta-dicalcium silicate. One is manganese blast furnace slag, with Mn melilite and a substantial sulphide content.

Minor adherent quartz sand present.

CONCLUSION

These samples are mainly steel slags and most contain both free lime and periclase. Generally, however, the slags have a fresh appearance with little signs of alteration. Two samples contain subsidiary amounts of brick and blast furnace slag.

The mineralogy of the steel slags is summarised in Table 2.