

REACTIVE MAGNESIUM OXIDE CEMENTS

Technical Field of the Invention

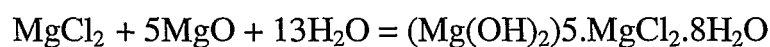
This invention relates to magnesium cements and in particular to cements containing magnesium oxide (magnesia).

5 Background to the Invention

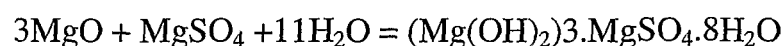
A number of cements based on magnesia have previously been made. If a salt such as magnesium chloride or sulphate is added to reactive magnesia and the mixture is allowed to react and hydrate magnesium oxychlorides and magnesium oxysulphates are formed that can be very strong but are not
 10 sufficiently weatherproof and are corrosive. Although there are many patents describing improvements to overcome these deficiencies such as the use of phosphates or soluble silicates, they are not generally economic.

Magnesium oxychlorides were first discovered and prepared by Sorel in 1867. Magnesium oxysulphates were discovered by Olmer and Delyon in 1934 .
 15 Magnesium oxychlorides and oxysulphates are commonly referred to as Sorel cements.

A number of compounds are formed when magnesia reacts with magnesium chloride to form oxychlorides. The main bonding phases so far found in hardened cement pastes are $\text{Mg}(\text{OH})_2$, $(\text{Mg}(\text{OH})_2)_3 \cdot \text{MgCl}_2 \cdot 8\text{H}_2\text{O}$ and
 20 $(\text{Mg}(\text{OH})_2)_5 \cdot \text{MgCl}_2 \cdot 8\text{H}_2\text{O}$. $(\text{Mg}(\text{OH})_2)_5 \cdot \text{MgCl}_2 \cdot 8\text{H}_2\text{O}$ has superior mechanical properties and is formed using a molar ratio of $\text{MgO}:\text{MgCl}_2:\text{H}_2\text{O} = 5:1:13$



If magnesium sulphate is used instead four oxysulphate phases are considered to form at temperatures between 30 and 120°C;
 25 $(\text{Mg}(\text{OH})_2)_5 \cdot \text{MgSO}_4 \cdot 3\text{H}_2\text{O}$, $(\text{Mg}(\text{OH})_2)_3 \cdot \text{MgSO}_4 \cdot 8\text{H}_2\text{O}$, $\text{Mg}(\text{OH})_2 \cdot \text{MgSO}_4 \cdot 5\text{H}_2\text{O}$, and $\text{Mg}(\text{OH})_2 \cdot 2\text{MgSO}_4 \cdot 3\text{H}_2\text{O}$. Only $(\text{Mg}(\text{OH})_2)_3 \cdot \text{MgSO}_4 \cdot 8\text{H}_2\text{O}$ is stable below 35°C.



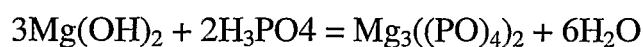
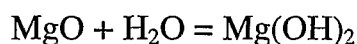
Zinc, calcium, copper and other elements also form similar compounds.

30 Magnesium oxychlorides achieve higher compressive strengths than magnesium oxysulphates. The main problem with Sorel cements is that both

magnesium oxychlorides and magnesium oxysulphates tend to break down in water and particularly in acids. Corrosion of steel reinforcing also occurs.

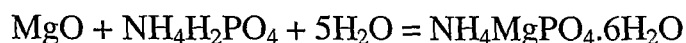
The use of soluble silicates such as sodium silicate has been described as a means of improving the water resistance of Sorel type cements. These cements
5 are of little practical use however because of the high cost of soluble silicates.

Magnesia reacts with soluble phosphates to precipitate almost totally insoluble magnesium phosphate.



10 The use of phosphates has also been advocated as a means of improving the water resistance of Sorel type cements. Such cements, although described in the literature, are expensive due to the shortage of economic deposits of phosphate and as a result widespread use is limited.

A range of magnesium phosphate cements has been used including
15 magnesium ammonium phosphate which is thought to be formed by an acid-base reaction between magnesia and di hydrogen ammonium phosphate. This results in an initial gel formation followed by the crystallisation into an insoluble phosphate, mainly magnesium ammonium phosphate hexahydrate, $[\text{NH}_4\text{MgPO}_4 \cdot 6\text{H}_2\text{O}]$. The magnesium oxide used in this system is produced by
20 calcining at higher temperatures and is referred to in the industry as being "dead burned" and is not as reactive as magnesia made at lower temperatures. A set retarder, typically either borax or boric acid is also used to give a workable set time.



25 High-lime magnesiochrome cement finds use in refractories. The cement is based upon magnesia plus calcium chromate - chromite, a complex mineral produced by the combination of lime with chrome oxide (Cr_2O_3) in an oxidising environment. Hydration is normally performed with a 30% aqueous solution of magnesium chloride hexahydrate ($\text{MgCl}_2 \cdot 6\text{H}_2\text{O}$) solution at 8 per cent by weight
30 of the cement. The products are complex. As well as hydrates they also consist of carbonates, which are formed by the effects of carbonation. Typical products

formed can include brucite $[\text{Mg}(\text{OH})_2]$, various magnesium oxychlorides $[(\text{Mg}(\text{OH})_2)_x.\text{MgCl}_2.y\text{H}_2\text{O}]$ calcium chromate dihydrate $(\text{CaCrO}_4.2\text{H}_2\text{O})$, calcium monochromite $(\text{CaCr}_2\text{O}_4)$ portlandite $[\text{Ca}(\text{OH})_2]$, secondary magnesium carbonate (MgCO_3) , secondary calcium carbonate (CaCO_3) and mixed calcium
5 magnesium carbonates $[(\text{Ca},\text{Mg})\text{CO}_3]$.

Other known cementitious magnesia compounds include hydroxychlorides and sulphates such as $\text{Mg}(\text{OH})_2.\text{MgCl}_2.8\text{H}_2\text{O}$, hydroxy carbonates $[\text{Mg}_5(\text{OH})_2(\text{CO}_3)_4.4\text{H}_2\text{O}]$ and hydroxy chloro carbonates [e.g. $\text{Mg}_2\text{OHClCO}_3.3\text{H}_2\text{O}$] as well as hydro magnesite and magnesite.

10 Brucite $[\text{Mg}(\text{OH})_2]$ alone has not found much commercial use as a cement previously mainly because the setting rate is too slow.

Summary of the Invention

The invention provides in one form a cement composition that includes reactive magnesium oxide at a level of at least 5% w/w of hydraulic
15 cementitious components. Preferably the magnesium oxide is prepared by low temperature calcination and fine grinding.

Other cementitious components can include any hydraulic cement including Portland type cements, calcium aluminate cements, alinite cements, belinite cements, belite cements, hydrogarnet cements and ferrari cements as
20 well as other magnesium cements such as Sorel cements. Pozzolans (including wastes) and fillers are not regarded as hydraulic cementitious components in this specification. Sorel cements include water in their composition and are therefore considered as hydraulic cements.

Preferably the composition further includes at least 10% of a pozzolan.

25 Preferably the hydraulic cement composition includes ground Portland cement clinker type minerals.

Detailed Description of the Invention

The present invention provides cement compositions containing substantial proportions of reactive magnesia that hydrates to form brucite which
30 is a useful cementitious component. They generally but not always contain a high proportion of pozzolans, many of which are wastes such as fly ash.

The compositions include the blending of reactive magnesia with hydraulic cements, preferably Portland cements but also other cements including other magnesium cements and/or the use of various accelerators as a means of improving the setting and hardening times and early strength. Both
5 blending with other cements and the use of accelerators as formulation strategies can be used independently, or sometimes combined to advantage rendering brucite useful as a binder in a cement matrix.

When other commercially useful cements are blended with reactive magnesia in the formulations provided for in this invention ultimate strength is
10 also improved. The magnesia in turn provides a virtually insoluble matrix of high pH in which most other cements are stable and affords a degree of protection in normally aggressive solutions such as sulphates.

The blending of reactive magnesia (MgO) with ground Portland cement clinker or more specifically ground mineral products from the calcining of
15 mixtures of limestone and clays or other sources of calcium, silica and aluminium used in the manufacture of Portland cement, such as di calcium silicate [Ca_3SiO_5 or alite (in nature hatrurite)], tri calcium silicate [Ca_2SiO_4 or belite (in nature larnite), tri calcium aluminate [$\text{Ca}_3\text{Al}_2\text{O}_6$], ferrites [e.g. $\text{Ca}_3(\text{Fe,Al})\text{O}_6$] and free lime $\text{Ca}(\text{OH})_2$ either in a blend (such as Portland
20 cement) or individually has been discovered to be a good strategy for improving the rate of strength gain and ultimate strength of cements based on reactive magnesia as a mineral binder.

Although virtually any proportion can be used effectively, it has been observed that at even a very high ratio of 80 - 98 % of a pozzolan such as fly ash with 2 -
25 20% reactive magnesia and ground Portland clinker hardens well. The magnesium oxide and ground Portland clinker weight ratio may vary depending on the rate of strength gain and ultimate strength required or desired sustainability. Typically the ratio of reactive magnesia to ground Portland clinker is in the range 1:3 to 2:1. Higher proportions of the magnesia – Portland
30 component result in more rapid setting times, particularly when the ratio of Portland cement to reactive magnesia is also higher.

The addition of pozzolans is not necessary as a strong cement is produced by merely blending Portland cement clinker minerals and reactive magnesia. However, they are useful as they have, most often only when activated, but sometimes depending on their composition without activation, cementitious properties. They also serve to mask the slower setting times of the magnesia component, preventing structural defects and if they are also wastes, they reduce costs.

The use of accelerators is both an additional and alternative technique to improve early setting and hardening times. If accelerators such as ferrous sulphate are used whether with blends of reactive magnesia and pozzolans alone (an alternative technique) or also with other cementitious components (an additional technique) they are added in small proportion only (less than 20% of the MgO proportion).

A particular embodiment of the strategy of blending magnesia with Portland clinker minerals was made with the following proportions that achieved high strengths in the order of 12-20 mpa after pre curing for 48 hours followed by steaming at 55°C for 48 hours and then further curing for a period of three weeks.

The composition was made by mixing as dry powders 600 g (94% by weight) fly ash from the Gladstone power station in Australia, 30 g (4.67 % by weight) reactive magnesia ground to 95% passing 45 micron and 100% passing 125 micron (branded as XLM and from Causmag in Australia) and 12 g (1.87 % by weight) ground Portland cement clinker ground to 100% less than 125 micron from Australian Cement in Railton Tasmania. Water was added to make a stiff paste and this was then vibrated into moulds. After approximately six weeks the sample reached a strength approaching 20 mpa and was resistant to sulphates and other solutions aggressive to Portland cement.

Portland cements containing magnesium oxide are currently termed “unsound” and the use of limestones containing magnesium for making Portland cements is avoided. The reason why is because when magnesite or dolomite, present as an “impurity” contained in limestone, is slaked at high

temperatures during the manufacture of Portland cement, a highly unreactive oxide termed "dead burned magnesia" is produced which hydrates long after other cementitious components when water is added.

- 5 Magnesite (MgCO_3) begins decomposing to the oxide at a substantially lower temperatures and pressure than limestone (CaCO_3) This is true of mixtures of limestone and magnesite as well as for the distinguishable mineral dolomite which contains both magnesium and calcium as carbonates.

Reaction	Atomic No. of metal	Enthalpy ΔH° (kcal)	Entropy ΔG° (kcal)	T($\text{PCO}_2=$ 1atm)
$\text{MgCO}_3 = \text{MgO} + \text{CO}_2$	12	28	16	540°C
$\text{CaCO}_3 = \text{CaO} + \text{CO}_2$	20	42	31	900°C

- 10 Portland cement is typically made between 1450°C and 1500°C. At these temperatures any magnesium carbonate content becomes unreactive due to the formation of larger more defined crystals with less surface area and lower porosity than at lower temperatures. Magnesia produced in this manner, referred to as 'dead burned', is unreactive and hydrates very slowly - usually long after
- 15 the other components in a cement such as Portland cement have hydrated. As a result stresses are introduced resulting in what is often termed unsound cement. Because of this magnesium oxides have been condemned for many years in Portland cement. Unreactive magnesia is also unsuitable for use in the present invention.

- 20 The key for the successful blending of magnesia and other cements and in particular Portland type cements is that the hydration rates of all components in the cement must be matched. In order to achieve this the magnesia component must be separately calcined at lower temperatures and in conditions that are suitable for the manufacture of reactive magnesia, ground to a fine size
- 25 depending on the reactivity required and only then blended with other cementitious components, pozzolans or both.

Suitable magnesia should be calcined at low temperatures (less than 750°C) and ground to greater than 95% passing 120 micron. Generally the lower the temperature of calcination and finer the grind, the more reactive the magnesia is and the faster it hydrates. Magnesia calcined as 650 °C passing 45
5 micron or less is better.

A test for reactivity is the citric acid test and low temperature calcined magnesia ground to 95% passing 45 micron tests at about 10 seconds using this method which uses .5g sodium benzoate, 28g citric acid monhydrate and .1g phenolphthaleim dissolved in water and diluted to 1 litre.

10 If the above small amounts of sodium benzoate and phenolphthaleim do not dissolve, a small amount of methylated spirits should be used as well. The prepared solution is stored in a water bath at 30°C ± 0.2 C.

The test method is to first weigh a 2.00g sample of magnesia on a watch glass. Then Pipette 100ml of the prepared solution in to a dry 250ml tall form
15 beaker. Add the 2.00g powder sample previously weighed and stir (preferably with a magnetic stirrer) immediately. Record the time in seconds for the stirred solution to turn pink.

The reactivity and hydration rates of hydraulic cements, and in particular Portland clinker products, magnesia and lime are affected by the temperature
20 and conditions of calcining as well as the particle porosity, texture and size and the porosity, texture and size of interspersed components such as pozzolans including fly ash and can therefore be engineered to match mainly by varying slaking temperatures and grind sizes.

It is important that volume changes are approximately neutral to prevent
25 structural defects occurring during setting and volume changes are related to reactivity.

Consider the volume changes that occur when magnesia hydrates:



$$11.2 + 18.0 = 24.3 \text{ molar volumes.}$$

30 If this reaction is slow as is the case with “dead-burned” magnesia produced as a result of high temperature calcining it occurs after all the free

mixing water has been taken up by hydration of other cementitious minerals. For example, during the manufacture of Ground Portland clinkers, the main minerals produced are alite and belite. Alite hydrates more rapidly than belite however hydration proceeds much more rapidly with both than for the “dead
5 burned” magnesia component present as an impurity contained in limestone for example. All the free moisture is used up before hydration of magnesia can proceed to completion and for the reaction to proceed then moisture must be absorbed by the mass over and above the original mixing water resulting in a net volume increase of $24.3 - 11.2 = 13.1$ molar volumes hence the cracking that
10 occurs and the bad name that magnesia contained as an impurity in Ground Portland clinkers has obtained.

If finely ground magnesia that is highly reactive is added after the calcining process required for the manufacture of most other cements such as Portland cement, the same hydration reactions occur but much more rapidly. As
15 a result the moisture is absorbed more rapidly and mainly from the mix water and there is no net absorption of moisture that was not contained in the original mix. In terms of molar volumes from the above equation, $\text{MgO} (11.2) + \text{H}_2\text{O} (18.0) = \text{Mg}(\text{OH})_2 (24.3)$. the volume of the reactants is more than the products by some 4.9 molar volumes, and this small amount is taken up from pore water.

20 It is desirable with the composition of the present invention to maintain a moist environment particularly after the first few hours curing and it has been determined that approximately neutral volume changes result if this is the case resulting in little or no stresses that have to be accommodated.

The hydration of reactive magnesia added during the final blending or
25 grinding stages of the manufacture of a cement is sufficiently rapid to allow most volume adjustments that there are to occur before restraining strength is achieved by the other cementitious components preventing stresses from developing that cause structural defects.

As the magnesia component of the cements provided for in this invention
30 hydrates, brucite is formed which is highly insoluble ($K_{sp} 1.8 \times 10^{-11}$, equivalent to .018g/litre) and it blocks off access to water for further hydration.

The addition of pozzolans such as fly ash tends to reduce the amount of brucite that needs to form for strength to develop and negates the blocking off affect of the advancing brucite reaction front as well as taking up minute volume changes (if any) and acting as a microaggregate at a microscopic level.

5 Pozzolans including natural pozzolans and artificial pozzolans such as fly ash and other wastes also react with the free lime component included in Portland cement clinker products and formed as a result of the hydration of calcium silicates to produce more calcium silicates that also hydrate and further bond the components of the cement together.

10 Inter particle surface interaction also results in chemical as well as physical bonding between fine grains of pozzolan and other cementitious components and between the pozzolan grains themselves. This is mainly due to hydration reactions but also surface hydrolysis and geopolymeric reactions particularly if an alkali such as provided by the more soluble portlandite phase
15 (Portlandite or calcium carbonate has a K_{sp} of 5.5×10^{-6} or solubility of 1.37 g/litre) of Portland cement is present.

 These reactions occur later during the hardening of the cements described by this specification as the more soluble alkalis become concentrated as other cement components such as calcium silicate and magnesia hydrate and use up
20 mixing water.

 The grains of pozzolan also provide nucleation sites for the hydration of other components of the cement.

 In this specification the term pozzolan is used to described materials containing silicon and aluminium that react with or are activated by an alkali,
25 and in the presence of water form stable silicon and aluminium compounds.

 There are two basic kinds of wastes and both can effectively be used with the compositions of the present invention.

 Wastes which are pozzolans and which contribute to strength given the longer term or shorter periods if accelerated by accelerators also described or by
30 heating preferably in a moist environment. Examples are wastes produced by the agriculture and mining industry in increasing amounts such as reactive fly

ash, flue wastes, iron ore slag, and other wastes from the metal production industry as well as silica fume, ground brick, and sewerage sludge ash.

Passive wastes take no chemical part in the formation of a cement and include, sawdust, unburnt rice husks, some mine tailings, mineral extraction wastes etc. and virtually all may be used as fillers. A high proportion can be added without loss in strength and add to abrasion resistance (and in many cases workability). If fine enough they act as micro aggregates and often result in greater strength.

Of the pozzolanic wastes available in quantity cheaply, fly ash is economically the most important and has been found to make a slightly better cement when combined with magnesia than ground vitrified iron ore slag and the reasons for this could be that the heat treatment has been more appropriate and the silicon alumina ratio is closer to ideal proportions.

Ground bauxite or brick has been found to increase strength when added to mixtures of magnesia and fly ash. As mixtures of magnesia and silica fume hardly show any strength but mixtures of magnesia silica fume and bauxite do the increased reactivity due to the inclusion of bauxite is probably a function of the addition of alumina, but this has not been proven as it may also be due to a concentration affect.

It has also been found possible to include large amounts of waste containing alumina such as "red mud" which is a waste form the aluminium industry.

The best results with "red mud" have been obtained when ferrous sulphate was also added in small amounts (1-20% of the MgO proportion). As red mud contains soluble sodium compounds, particularly sodium carbonate, sodium sulphate is produced and could be effectively recovered. The carbonates remain as siderite, or alternatively combine with the magnesium forming magnesite and hydromagnesite.

Bauxite may also be used as a source of alumina depending on the alumina content of the primary waste and is available in large quantities at low cost. Bauxite consists mainly of gibbsite ($\text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$), boehmite ($\text{Al}_2\text{O}_3 \cdot \text{H}_2\text{O}$),

and diaspore, which has the same composition as boehmite but is denser and harder.

Sewerage sludge ash, besides being a source of reactive silica and alumina and therefore a pozzolan, is a rich source of soluble phosphates. The phosphates react readily with magnesia forming mostly stable insoluble phosphates which have good binding properties.

The residue from burning organic wastes such as rice husks is also reactive and may contain ideal quantities of silica and alumina.

The addition of gypsum, limestone and other additives normally used in Portland cement is usually unnecessary. As gypsum does not appear to be deleterious and may even have a small advantage as a set regulator for the Portland cement component, accelerator for the magnesium oxide component and flocculation agent, commercial Portland cement containing a small percentage of ground gypsum may be used as an alternative to pure ground Portland clinker materials in virtually any ratio.

The addition of ground limestone, often added to Portland clinker with which it has some reactions, has little or no affect to the reactive magnesia component and this is an advantage as it allows the use of impure magnesite for the manufacture of reactive magnesia for use pursuant to this invention. At the low temperatures used to produce reactive magnesia and particularly with the use of fluxes such as sodium fluoride or chloride, limestone does not react and remains unslaked and inert with respect to magnesia, acting merely as a filler.

Most sources of magnesia contain small quantities of calcium and normally at the temperatures at which reactive magnesia is calcined (550-750°C) the calcium remains as calcium carbonate which does not interfere with the setting of cements containing a high proportion of reactive magnesia described in this invention.

The differential decomposition of calcareous magnesite and dolomite can be of economic advantage, particularly if fluxes such as sodium chloride or fluoride are added. Both calcareous magnesite and dolomite can be slaked at temperatures insufficient to break down the calcium carbonate to make a mix of

magnesia and calcium carbonate suitable for the manufacture of cements described in this invention

Reactive magnesia added during the final stages of manufacture of other cements such as calcium aluminate cements, slag cements, Sorel cements and
5 geopolymeric cements etc. can also be an advantage.

As with Portland cement the key is to match the hydration rates and to do this reactive magnesia is required.

There are three main classes of accelerants that can be used in the composition of the present invention:

- 10 1. Alkaline chemicals which mobilise silica and alumina.
2. Acids and salts of acids.
3. Organic accelerators.

Alkaline chemicals that accelerate the setting of Portland cement include chemicals such as alkali and alkali earth hydroxides, carbonates, formates,
15 aluminates and silicates.

Small dosages of alkaline accelerants work with the composition of the present invention. If Portland cement is included in the blend they aid the formation not only of calcium aluminates but also of calcium silicates by mobilising silica and alumina, both of which are much more soluble in an
20 alkaline environment.

Some of the alkaline accelerants that have been tested are listed below in order of effectiveness.

Accelerant	Effectiveness (1-10)
Sodium aluminate	8
Sodium silicate	8
Sodium carbonate	7
Sodium hydroxide	2

The most effective in this group are sodium silicate and sodium aluminate, and of these sodium silicate is known to be an accelerator of geopolymeric reactions.

Another group of accelerants are acids and in particular soluble salts of acids and generally both the cation and anion contribute to the overall effect facilitating the dissolution of magnesia and lime. Although early setting is accelerated long term strength is generally reduced.

According to Rodney M Edmeades and Peter C Hewlett anions that cause significant acceleration with Portland cements are halides, nitrates, nitrites, formates, thiosulfates and thiocyanates. Their activity also appears to depend on the associated cation and research has shown that with Portland cement divalent and trivalent cations such as calcium, magnesium, barium and aluminium appear to be more effective than monovalent ions such as sodium, potassium and ammonium.

Other acidic accelerants not mentioned by the above authors include sulphates such as ferrous sulphate and calcium or aluminium sulphate.

A commonly used accelerant in this group with Portland cement used to be calcium chloride until usage was banned in many countries because of corrosion problems with reinforcing.

All of the above accelerants appear to work with the high magnesia cements that are the subject matter of this application having the effect of causing more rapid dissolution of magnesium hydroxide and in the case of blends with Portland cement, other cementitious components as well.

A number of salts have been tested and found to work in order of effectiveness as hereunder:

Accelerant	Effectiveness (1-10)
Calcium chloride	8
Ferrous sulphate	8
Potassium nitrate	8
Sodium sulphate	8
Calcium nitrate	8
Aluminium potassium sulphate	6
Sodium chloride	6
Aluminium sulphate	43

Of the above, one of the best and potentially the cheapest accelerators is ferrous sulphate. With accelerators that are salts of acids such as ferrous sulphate, it is important to note that initial setting may be accelerated, but the addition of too much does not contribute to longer term hardening and can be deleterious.

Good results have also been obtained with organic agents that hydrolyse silica and alumina and an example is triethanolamine.

In the case of Portland cement, triethanolamine works by combining with aluminium dissolving tricalcium aluminate prior to formation of tricalcium aluminate hydrate. Too much causes retardation of tricalcium silicate hydrate. With cements also containing reactive magnesia triethanolamine works in a similar manner by dissolving and mobilising aluminate.

Iron salts including sulphates and chlorides and in particular ferrous sulphate are the most recommended accelerants because of cost and environmental benefits as many of them are wastes.

As previously mentioned, reactive magnesia can be blended with a range of hydraulic and chemical cements and iron salts can also be used in many such blends including the commercially more important blends with ground Portland clinker minerals discussed. The quantity added should be kept as low as

possible to achieve the required initial set. Iron salts do not appear to contribute to final strength, and if too much is added this may even be reduced.

Ferrous sulphate is recommended in most instances because it is less aggressive than ferric sulphate or ferrous or ferric chloride for instance and also cheaper. A small percentage (.5 - 20 % of the MgO content) of ferrous sulphate is effective in accelerating the initial setting of cements made using a proportion of added reactive magnesium oxide and in particular with blends of such cements with pozzolans including pozzolanic wastes such as fly ash. The amount added depends on a number of factors including the reactivity of the magnesia and other components of the cement.

The specific role of iron salts is to speed up initial setting. Small quantities do not appear to affect final strength and hardness however if too much is added reactions are too rapid and cracking and increased susceptibility to weathering result.

It is believed that initially an acid base reaction takes place with the sulphate (or chloride) forming magnesium sulphate (or chloride) and in the presence of calcium, calcium sulphate (or chloride). This acid base reaction serves to mobilise the magnesium which ends up mostly as magnesium hydroxide (brucite). The iron initially forms a hydroxide but generally ends up in iron minerals such as haematite and magnetite. Iron is also bound into ferro brucite and amakinite and a number of other compounds.

The magnesium sulphate or chlorides formed then react with magnesium hydroxide resulting in compounds such as magnesium oxysulphates or oxychlorides that also act to bind the cement. In the medium and longer term the continued hydration of brucite takes over as the principle setting mechanism depending on the proportions.

A major advantage of using iron salts and in particular ferrous sulphate as accelerants is the low cost of the salts. Ferrous sulphate is also not anywhere near as hygroscopic as either magnesium sulphate or magnesium chloride used in the manufacture of Sorel cements and in a dry atmosphere it can be ground to a fine size enabling the economical production of "all in the bag" mixes.

Experiments have shown that with cements containing a high proportion of reactive magnesia small quantities (.5 to 20% of the MgO content) of ferrous sulphate reduces setting times considerably and it is possible to cause such cements to set with sufficient moulding strength (.5-5 mpa) within just a few hours. Some other sulphate or chloride salts of elements with a similar ionic radius to iron and of similar charge have a similar affect but are not cost effective. e.g salts of manganese.

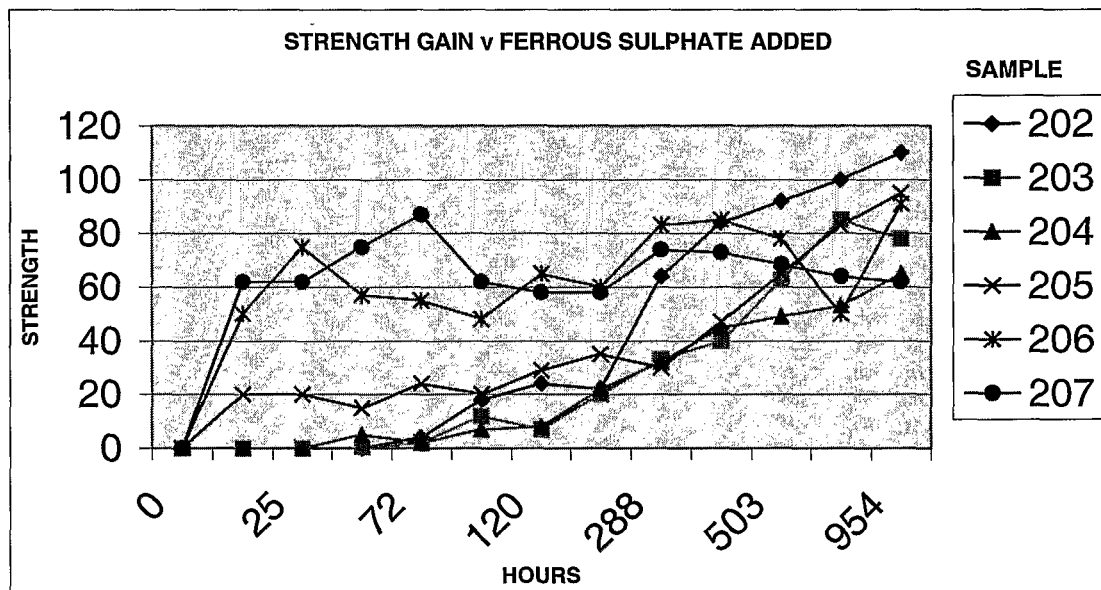
Ferric sulphate reacts with magnesia more aggressively than ferrous sulphate and therefore whether ferrous or ferric sulphate is used depends on the reactivity of the magnesia (which in turn depends on slaking temperature, particle size and age) and other materials added. The same applies to ferrous and ferric chloride, but costs and comparative lack of strength do not favour their use except when stronger magnesium oxy-chloride cements are to be modified by the inclusion of iron.

It is recommended that the amount and type of iron salt added is determined by trial and error as the reactions in the case of pure magnesia depend on the reactivity of the magnesia, particle size etc. and if pozzolans including wastes such as fly ash are also added, are heavily masked. Other blended wastes may also have a masking affect and more or less quantity or more or less aggressive iron salts may need to be used depending on the nature of the waste, be it fly ash, sewerage ash, rice husks etc all of which vary in reactivity. As the reaction of magnesia with iron salts is exothermic, and can get too warm if too much iron salt is added, care needs to be taken. Whether or not steam or autoclaving is also used needs to be considered as reaction rates roughly double with every 10 deg. rise in temperature, whereas increases in pressure do not have quite such a marked affect.

The use of iron salts is more advantageous with less reactive magnesia - again depending on the reactivity of other ingredients and the quantity added needs to be increased accordingly. Magnesia reactivity can be effectively measured using the citric acid test discussed earlier.

A simple experiment illustrates the affect of the addition of small amounts of ferrous sulphate to a cement made with magnesia and fly ash. Several samples were compared for strength over a period. Each sample was made with 50% fly ash and the balance was reactive (citric acid test 22 seconds) magnesia ground to 95% less than 45 micron and 100% less than 125 micron with ferrous sulphate at ratios given in the table.

The graph below shows strength on the vertical axis determined on an apparatus for measuring comparative compressive and shear strength on an arbitrary linear scale. (The scale is arbitrary in that it has not been equated to standard test units. The results produced by the apparatus are however very consistent and thus can be used for comparison purposes.) The horizontal axis is time.



Sample	202	203	204	205	206	207
FeSO ₄ /MgO	0	3.45%	7.14%	15.38%	25.00%	36.36%

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As can be seen from the graph, at around a 15% FeSO₄ /MgO (sample 205) strength gain was achieved in the first few hours as compared to pure brucite (sample 202) which did not gain strength for several days.

The cementitious minerals forming in the above example include brucite, ferro brucite, amakinite, iron oxysulphate, magnesium (iron) oxysulphate (see

20

below) haematite and magnetite and near the surface, where access to CO₂ is possible, hydromagnesite and magnesite and a magnesium hydroxy sulpho carbonate. Ultimately silicates and aluminates, and their hydrates form very slowly.

5 Brucite is the main cementing phase and the structure consists of layers of hydroxyls with magnesium in between. Fe⁺⁺ substitutes for Mg⁺⁺ in brucite forming a mineral known as akmanite and this may even be slightly stronger than brucite. A fine dispersion of magnetite (Fe₃O₄) also often occurs in the structure, possibly also adding to strength.

10 It has been found that the addition of iron salts is compatible with Sorel cements as well as Portland and many other hydraulic cements. Ferrous sulphate or ferric sulphate are most compatible with magnesium sulphate forming a magnesium oxysulphate cement that contains haematite. Iron may also be present as an oxysulphate and may substitute for magnesium in magnesium
15 oxysulphates.

 Generally iron chlorides blend best with magnesium chloride and iron sulphates with magnesium sulphate, however, as in the case of Sorel cements where the addition of magnesium sulphate and magnesium chloride can be mixed, mixtures of both iron sulphate and magnesium chloride or iron chloride
20 and magnesium sulphate set effectively, and can be an advantage if calcium is also present as the calcium hydroxide formed reacts with the sulphate forming calcium sulphate which in turn reacts with magnesium hydroxide producing more Sorel cement.

 When a pozzolan such as fly ash or an alternative source of reactive
25 silica and alumina is added to cements containing reactive magnesia (with or without added iron salts or salts used for making Sorel cements) the pozzolan reacts in a number of ways previously discussed including reacting with any free lime producing more calcium silicate hydrates if free lime is present such as caused by the addition of Portland clinker as well as surface hydrolysis and
30 geopolymeric reactions occurring.

Other reactions also occur very slowly involving Mg^{++} and Fe^{++} as a suitable environment is formed in which the very slow formation of magnesium (iron) silicates and aluminates occurs. Some minerals formed are not of great strength and are almost gel like such as sepiolite, others are weak such as hydrotalcite and talc but others such as enstatite and forsterite are strong minerals.

With rising temperatures through the application of heat using steam for example, many of these reactions proceed more rapidly.

Soluble silicates and aluminates can also be added to advantage encouraging the formation of silicate and aluminate minerals but cost will generally rule out the use of these materials.

Long term strength gain continues in a cement made predominantly from reactive magnesia and is accelerated by moderate heat. (Reaction rates very roughly double with every 10 degree rise in temperature.) As too much heat will decompose $Mg(OH)_2$ and water provides a medium for reaction and encourages further hydration reactions including the hydration of magnesia, the use of steam is ideal.

Another advantage of the compositions of the present invention are that they are able to accommodate a wide variety of extraneous cations and anions. Many of these extraneous cations and anions are thought to find their way into the open layered structure of brucite, where if they are toxic, they are rendered inert as long as the brucite does not dissolve.

Because of the high insolubility of brucite, the compositions of the present invention are generally not attacked by soft waters. Surface protection by carbonates ensues with most acid rains.

The high reactive magnesia cement compositions described are also very resistant to sea and ground water attack and this is thought to be because brucite, the main component, is virtually insoluble at the pH of sea water (8.2) and in most ground waters and does not suffer ion replacement or decomposition in the same manner as the calcium silicate hydrate found in Portland cement as portlandite is replaced or leached out.

Tests have confirmed resistance to agents such as glaubers salts, epsom salts, sodium chloride, ammonium nitrate and weak organic acids.

The use of several plasticisers has been tested including Neosyn EA which is a sodium salt of naphthalene sulphonic acid polymer with formaldehyde. These appear to work in a manner similar to Portland cement affecting surface charge however in most situations they do not seem to be needed.

In an experiment to reduce the attack by microbes on the high magnesia cements provided for in this specification, copper sulphate was added in small proportions (Less than 5% of the MgO content). It was found that adding copper sulphate in small proportions to mixtures of magnesium oxides and water and magnesium oxides, ground Portland cement clinker and water had a slowing down affect on setting and could therefore be useful as a set retarder for special cements such as required for drill holes.

Other experiments with the purpose of providing higher early strength and reducing initial setting times included the addition of organic polymers and resins. In particular the addition of polyvinyl acetate (PVA), vinylacetate-ethylene, styrene-butyl acrylate, butyl acrylate-methylacrylate and styrene-butadiene were found to be beneficial as well as liquid rubber (latex). Some resins were also tested and found to be beneficial, but with all of these organic additives there is some trade off because of cost.

1. A hydraulic cement composition that includes reactive magnesium oxide at a level of at least 5% w/w of hydraulic cementitious components in the composition excluding pozzolans.
- 5 2. A hydraulic cement composition as defined in claim 1 that includes Portland cement.
3. A hydraulic cement composition as defined in claims 1 or 2 that includes Sorel cements.
- 10 4. A hydraulic cement composition as defined in any one of claims 1 to 3 which includes calcium aluminate cements.
5. A hydraulic cement composition as defined in any one of claims 1 to 4
15 which includes a pozzolanic material.
6. A hydraulic cement composition as defined in claim 5 wherein the pozzolanic material includes fly ash.
- 20 7. A hydraulic cement composition as defined in any one of claims 1 to 6 wherein an accelerator being an acid or the salt of an acid is further included.
8. A hydraulic cement composition as defined in any one of claims 1 to 6 wherein an iron salt is included as an accelerator.
- 25 9. A hydraulic cement composition as defined in claim 8 wherein the iron salt is ferrous sulphate.
10. A hydraulic cement composition as defined in any one of claims 1 to 9
30 wherein sodium or potassium silicate or aluminate is included as an accelerator.

11. A hydraulic cement as defined in claim 1-10 which is heated or steamed at temperatures in the range 20 - 1000°C.
12. A hydraulic cement composition as defined in claim 1 - 11 wherein the composition further includes soluble phosphates.
13. A hydraulic cement composition as defined in claim 12 wherein the soluble phosphate is phosphoric acid or phosphoric acid salts.
14. A hydraulic cement composition as defined in any one of claims 1 to 13 that further includes a set retarder.
15. A hydraulic cement composition as defined in claim 14 wherein the set retarder is copper sulphate.
16. A hydraulic cement composition as defined in any one of claims 1 to 15 that further includes organic polymers and resins.
17. A hydraulic cement composition as defined in claim 16 wherein the organic polymer is polyvinyl acetate (PVA), vinylacetate-ethylene, styrene-butyl acrylate, butyl acrylate-methylacrylate, styrene-butadiene or latex.