# A Review of Magnesium Oxide in Concrete

## A serendipitous discovery leads to new concrete for dam construction

BY CHONGJIANG DU

MgO concrete was developed by Chinese dam engineers and has been applied predominantly in the construction of concrete dams in Chinese-speaking regions. It has been successfully used in about 30 dams over the past three decades and remarkable results and experiences have been collected. However, knowledge of this novel material and technology is not widespread in other countries.

Magnesium oxide-based shrinkage-compensating concrete (MgO concrete) is concrete with an additive of lightly burnt MgO powder. When MgO hydration takes place, the final product is magnesium hydroxide, $Mg(OH)_2$. Because $Mg(OH)_2$ has a larger volume than its constituents, MgO concrete is expansive. Concrete made with more typical expansive cements like ASTM C 845[1] Types M, K, and S expand at early ages. However, most of the volume expansion of MgO concrete occurs at late ages (after 7 days). The expansion of MgO concrete therefore closely matches the shrinkage of mass concrete as it cools, and the concrete has been of particular interest in construction of dams to minimize crack development, simplify temperature-control measures, and speed up construction.

### A BRIEF HISTORY

The shrinkage-compensating effect of MgO concrete was discovered by chance. The Baishan concrete arch gravity dam in Northeast China was constructed during China's "Cultural Revolution" (1966-1976), when technical regulations and standard engineering practice could not be implemented for dam construction. As a consequence, temperature-control measures for mass concrete were not taken seriously during construction of the dam.

Most of the base concrete was placed during the summer, and the differential between the maximum temperature rise and the stable temperature of the concrete was over 40 °C (72 °F). However, no significant cracking was detected in the dam concrete, even though it later experienced severe cold weather conditions. This astonished the dam builders. Engineers traced the phenomenon and found that the main and only possible factor was that the content of MgO in the cement used was high (up to 4.5%), and the burning temperature of the cement was relatively low. The conclusion was that lightly burnt MgO is reactive, provides a long-term expansive effect that occurs from 7 to 1000 days after the concrete hardens, and does not lead to unsound concrete. The study and intentional application of MgO concrete started from this point on.

### FUNCTIONS OF MgO CONCRETE

In general, shrinkage compensation by autogenous expansion of the concrete has the following two effects:

- Precompressive stresses are produced at early ages in concrete structures with restrained boundary conditions. This can partially compensate for tensile stresses caused by cooling at later ages; and
- Long-term autogenous expansion at later ages compensates for contraction due to cooling and shrinkage. This directly reduces the tensile stresses in the concrete.

It should be noted that, because the autogenous expansion is globally uniformly distributed, the compensating effect holds only for tensile stresses caused by the external restraints. Furthermore, due to plastic deformation and creep of concrete, only the reversible part of precompressive deformation can take part in compensating for the tensile stresses at late ages. In fact, because the early age volume expansion of MgO concrete is relatively small, the precompressive stresses in the structure are insignificant, while the effect of its long-term expansion is predominant.

In dam construction, the foundation, lift joint surfaces, and dam abutments provide the external restraints. In addition, external restraint in the longitudinal direction can also be obtained by placement of concrete without transverse joints, which will result in continuous construction for the full length and width of the dam. Because of the expansive effect while the concrete temperature is dropping, the thermal tensile stresses, and thus the risk of concrete cracking, will be considerably reduced. This can significantly simplify temperature control measures, thereby reducing construction time and cost.

## PROPERTIES OF MgO CONCRETE

From long-term research and observation, it has been found that adding MgO powder to concrete will influence the mechanical properties, but have very little effect on thermal properties. Long-term studies have demonstrated that because the hydration process is irreversible and the $Mg(OH)_2$ is stable, the mechanical behavior of MgO concrete is stable.[2,3]

### Autogenous expansion

Autogenous expansion of MgO concrete depends on the type of MgO powder and is proportional to the quantity of powder added and the temperature of the concrete.

The magnitude and process of expansion depend on the burning temperature of the MgO powder, as described in the sidebar on the following page. The higher the burning temperature, the smaller the magnitude of early-age expansion and the longer the MgO hydration process lasts. Because the hydration of MgO is a gradual and irreversible process, the $Mg(OH)_2$ is stable, and its expansion is stable and not unlimited.

Free lime in cement will reduce the expansion of MgO concrete. Therefore, the free lime content should be kept to a minimum.[4] The magnitude of expansion is also proportional to the temperature of the concrete,[3,5] as shown in Fig. 1.

Therefore, with proper specification of the type and quantity of MgO powder and control of the concrete temperature, the magnitude of autogenous expansion of MgO concrete can, in turn, be controlled.

### Strength and modulus of elasticity

Both compressive and tensile strengths of MgO concrete are higher than those of conventional concrete. The increase in strength will be greater as the quantity of MgO powder added, curing temperature, and age of concrete increase.[2,6] Higher curing temperature increases the hydration rate of the MgO. As a result of more sufficient hydration, the microstructure becomes much denser. As a result of more expansion, the number of microcracks decreases. Adding MgO powder also reduces the overall water-cementitious materials ratio of the concrete, which may partially explain the observed increase in strengths.

Corresponding to the increase in strength, the modulus of elasticity of MgO concrete is slightly higher than that of conventional concrete, although its increase is less than that of strength. A higher modulus of elasticity generally increases concrete cracking, which should be kept in mind.

### Tensile strain capacity

Similar to compressive strength, the tensile strain capacity of MgO concrete increases with increased MgO powder content and curing temperature. For instance, the tensile strain capacity of concrete with an MgO content of 4.5% will increase by 19, 24, and 28% as the curing temperature increases from 20 °C (68 °F) to 30, 40, and 50°C (86, 104, and 122 °F), respectively,[2] and usually ranges from about 80 to 150 microstrain. The increase in tensile strain capacity is favorable to the cracking resistance of concrete. Tensile strain capacities of MgO concrete with 4.5% MgO powder under different curing temperatures are shown in Fig. 2.[7]

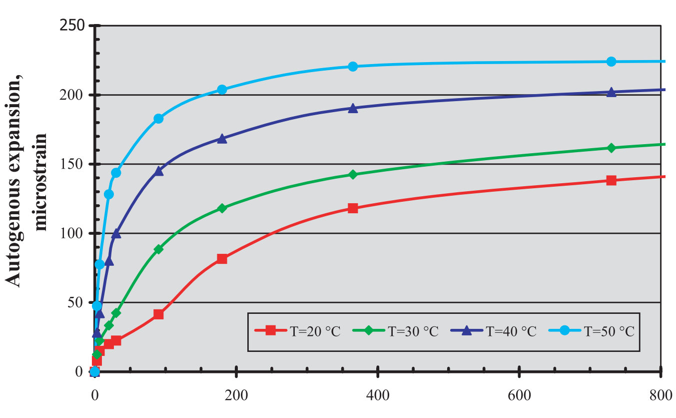


Fig. 1: Autogenous expansion of MgO concrete containing portland cement, 30 % fly ash, and 4% MgO

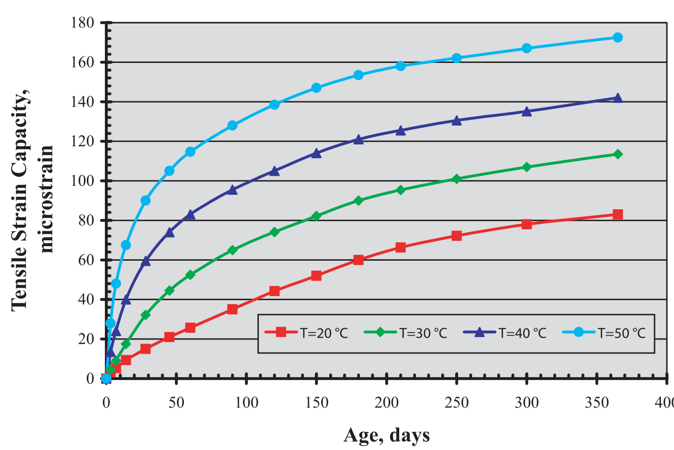


Fig. 2: Tensile strain capacity of MgO concrete containing portland cement and 4.5% MgO

## Creep

Long-term laboratory tests of MgO concrete[2] have shown that creep varies with time and loading. However, the magnitude of creep of 3.5 to 4.5% MgO concrete is about 20 to 25% more than that of the conventional concrete with the same mixture proportions. Therefore, the expansive effect of MgO will also result in increased creep, which is favorable to relax the tensile and compressive stresses and increase the cracking resistance of the concrete.

## Impermeability and abrasion resistance

For the same reasons as strength increases, the impermeability also increases by 0.6 to 7 times, depending on the restraint provided by the boundary conditions. Furthermore, studies[2] have indicated that, due to the increase in its strength, the abrasion resistance is about 7 to 10% higher than that of conventional concrete.

# DAM DESIGN AND CONSTRUCTION

In principle, design and construction of MgO concrete dams are similar to that of other concrete dams. However, attention should be paid to several special aspects:

## Magnitude of expansion

The first question may be the required magnitude of autogenous expansion. Although it's different from case

## MgO AND ITS BEHAVIOR

MgO is usually obtained by burning $MgCO_3$ ore until the $CO_2$ is driven off. The theoretical decomposition temperature of $MgCO_3$ ranges from 600 to 650 °C (1110 to 1200 °F). In industrial production, however, the decomposition temperature is usually in the range of 800 to 850 °C (1470 to 1560 °F) to increase production efficiency.

When hydrated, the volume of the $Mg(OH)_2$ crystals formed from MgO is significantly larger than the sum of the volumes of MgO and $H_2O$ alone, resulting in autogenous expansion. For example, when MgO produced at a burning temperature of 1000 °C (1830 °F) is hydrated, the volume of $Mg(OH)_2$ will be over twice the sum of the volumes of MgO and water. Research indicates that the burning temperature of MgO is a key factor affecting its expansive performance, as the burning temperature directly influences MgO crystal size and specific surface area (Chui, Liu, and Tang 1992). Further, as burning temperature increases, the hydration rate of MgO decreases, as shown in Table A (Fang 2004).

Therefore, "dead-burnt" crystalline MgO (MgO with a slow reaction time with water), as periclase, is a harmful constituent in cement (Neville 1995). Excessive quantities of such MgO produce undue expansion during hydration at very late ages. This may cause unsoundness of the concrete and thus produce deleterious expansion that leads to disintegration of concrete. For this reason, most international standards limit the content of MgO in cement to a maximum of 4 to 6 %. However, only periclase is deleteriously reactive—under certain temperature ranges, lightly burnt MgO powder is harmless (Neville 1995).

For engineering purposes, the burning temperature of MgO is grouped into two classes (Li 1998): lightly burnt MgO with a burning temperature of 850 to 1200 °C (1560 to 2190 °F), and heavily burnt MgO with a burning temperature of 1500 to 1800 °C (2730 to 3270 °F). The MgO naturally contained in cement is usually burnt at a temperature of about 1450 °C (2640 °F) and belongs to the heavily burnt class. The MgO powder used as an additive in concrete is lightly burnt at around 1100 °C (2010 °F) (Chui, Liu, and Tang 1992; Li 1998) and exhibits expansion without deleterious effect. The magnitude of expansion can be controlled as well. In combination with appropriate design and construction of dams, this expansive effect can be used to compensate for the shrinkage of mass concrete.

TABLE A:
Hydration rate of MgO powder

| Hydration time, days | Burning temperature | | |
|---|---|---|---|
| | 800 °C (1470 °F) | 1200 °C (2190 °F) | 1400 °C (2550 °F) |
| 1 | 75.4% | 6.5% | 4.7% |
| 3 | 100% | 23.4% | 9.3% |
| 30 | — | 94.8% | 32.8% |
| 360 | — | 97.6% | |

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to case, experience in about 30 dams provides some reference values, namely, about 60 to 80 microstrain for roller-compacted concrete (RCC) gravity dams, 100 to 120 microstrain for RCC arched dams, and 130 to 170 microstrain for conventional concrete arch dams.[8]

The appropriate content depends both on the MgO powder itself and on the individual dam structure. It should be determined by means of laboratory tests and numerical simulation (such as finite element analysis). The usual dosage (not including the MgO contained in the cement) should be limited to a maximum of 5% of the weight of the cementitious materials. For soundness of the concrete, the maximum theoretical content of MgO (including MgO powder to be added and MgO contained in the cement) is about 8%.[8]

### Fly ash

By using MgO powder to achieve shrinkage compensation, the cementitious materials can be portland cement plus fly ash. The effect of autogenous expansion will not be significantly influenced by using fly ash if its content is limited, but it should be noted that substituting cement with fly ash will reduce the heat of hydration. The temperature rise of the concrete will, in turn, be lowered. Also, the addition of fly ash reduces the hydroxyl ions ($OH^-$), which affects the distribution of magnesium ions ($Mg^+$).[9] As a result, the autogenous expansion of the MgO concrete may be indirectly suppressed. Research and engineering practice have demonstrated that the maximum fly ash content should be maintained in the order of 30% for MgO concrete.[6,9,10]

### Uniformity

MgO powder is usually added as an additional material as a dry percentage of the cementitious material either in cement manufacture, at a site-batching plant, or by blending MgO clinker into the cement clinker before grinding them together. In any case, the MgO must be well distributed in the concrete. Uniformity is a "must" for this concrete. Uneven distribution of MgO in the concrete will lead to harmful expansion that may cause disintegration or severe cracking of mass concrete structures. By blending the MgO powder into the cement (or cement clinker) in cement manufacture, uniformity is usually ensured. However, experience has shown that it is not difficult to mix it directly at site-batching plants.

Two critical steps to ensure uniformity are weighing the MgO powder and the concrete batching procedure. Experience has shown that electronic scales with high accuracy, controlled by computer, are the best apparatus to weigh the MgO powder. All mixers for mixing conventional concrete are suitable for mixing MgO concrete; however, special attention should be paid to the sequence of batching the ingredients and mixing time. Two appropriate batching procedures that were used in past projects are given in Table 1.[11-13] The minimum mixing time should not be less than 4 minutes, which may be 1 to 2 minutes longer than for batching conventional concrete. Using these procedures, uniformity can usually be ensured.

No matter which method is adopted for adding MgO powder, precautions should be taken and routine checking for uniformity is necessary. Samples should be taken at both the discharge of the mixers and where the concrete is placed. The uniformity should be measured by means of chemical analysis and carried out by trained and experienced personnel using the proper equipment.

### Construction procedure

Similar to other types of shrinkage-compensating concrete for dam construction,[14] numerical analysis and experience have demonstrated that continuous placement without delays between the placement of lifts is the optimal procedure for achieving the maximum expansive effect. For construction of RCC dams with MgO, this procedure may not be a problem; however, for construction of conventional concrete dams, this procedure often can't be used due to the installation of reinforcement or other objects. Therefore, as a compromise, time intervals between lifts should be as short as possible.

### Curing and protection

Because autogenous expansion of MgO concrete depends on the temperature of the concrete, surface protection becomes more important in winter to prevent rapid heat dissipation and reduce the temperature gradient near the surface. During the summer, surfaces should be kept moist with water or fog. In this manner, a relatively uniform temperature and thus uniform expansion can be achieved. Protection materials, such as foamed polystyrene boards (25-mm [1-in.] thick) and polyethylene air-bubble sheets have proven suitable for dam construction. The insulation provided by these materials is excellent, their costs are reasonable, and they can easily be installed on the concrete surfaces.

## EXAMPLE APPLICATIONS

As mentioned previously, MgO was unintentionally contained in the concrete used in the Baishan arch gravity dam. Since the 1980s, MgO concrete has received intense study and application in dam construction. In the 1980s and the first half of the 1990s, field trials of this concrete were successfully conducted on structures such as cofferdams, foundation portions of dams, and backfilling for preformed channels of penstocks[15] where strong external restraints were maintained. From these trials, valuable results and experience have been obtained. Since 1998, this concrete has been used for the entire structure in a number of arch dams, and remarkable technical and economic benefits were attained. Table 2 lists several of the dams that have been constructed using MgO concrete.

It is worthwhile to mention the Changsha thin arch dam in southeastern China—constructed from January to April 1999. The addition of 3.5 to 4.5% MgO powder (on top of the 2.5 to 3.0% MgO contained in the cement) was used to achieve autogenous expansion of about 138 microstrain. The maximum and minimum air temperatures at the dam site were 36.8 and –1.8 °C (98 and 29 °F), respectively. The dam was constructed without transverse or longitudinal contraction joints. No special temperature-control measures were taken. No cracks were detected during or after dam construction. The experience of successful construction and operation of this dam demonstrates the effectiveness of MgO concrete for dams.

## BENEFITS

The following benefits should be emphasized:

- *Costs of dam construction*: Arch dams can be constructed without transverse or longitudinal contraction joints, saving formwork and thermal protection for the joint surfaces as well as joint grouting work. Post-cooling of concrete for grouting, by means of circulation of cooling water through embedded coils, is thus unnecessary. However, MgO powder itself is an additional cost, and the mixing time of the concrete increases. This requires a larger batching plant capacity. (It should be noted, however, that the use of MgO cement, in which the MgO powder [or clinker] is blended during manufacturing, will not extend the mixing time beyond that of conventional concrete.) Also, the additional uniformity control should be considered.
- *Reduced construction period*: Dam construction time can be saved through reduction of thermal control measures, reduction or total elimination of transverse and longitudinal construction joints and the related post-cooling and joint grouting, and reduction of the time interval between the placement of concrete lifts. The time savings will significantly reduce the costs of project management, labor, and financing.
- *Early project operation*: Depending on the purpose of the project, the benefits from power generation, irrigation, water supply, flood control, and navigation can be realized sooner.

Five recently completed arch dams constructed using MgO concrete in China have shown that construction time can be reduced by about 50%, compared to conventional concrete,[16] clearly showing the benefits of using MgO concrete in dam construction.

## DAM CONSTRUCTION EXPEDITED

MgO concrete provides a new way to increase the construction speed and economy of concrete dams and other mass concrete structures. Autogenous expansion of concrete with lightly burnt MgO powder is stable and occurs mainly at late ages. Experience and research have demonstrated that the long-term expansion can compensate for the shrinkage caused by cooling of the concrete or other

TABLE 1:
Appropriate batching procedures for MgO concrete

| Procedure 1 | Procedure 2 |
|---|---|
| 1. Add mixing water;<br>2. Add MgO powder and mix 1 minute to form a uniform suspension;<br>3. Add admixtures, if applicable;<br>4. Add fine aggregate;<br>5. Add coarse aggregate;<br>6. Add cement; and<br>7. Add fly ash. | 1. Add coarse aggregate;<br>2. Add cement;<br>3. Add fly ash;<br>4. Add fine aggregate;<br>5. Add MgO powder and mix 1 minute; and<br>6. Add water and admixtures, if applicable. |

TABLE 2:
Examples of MgO concrete dams

| Name of dam | Dam height, m | Crest length, m | Concrete volume, $10^3$ $m^3$ | Additive MgO, % | Cement, $kg/m^3$ | Fly ash, $kg/m^3$ | Autogenous expansion, $10^{-6}$ mm/mm | Year of completion |
|---|---|---|---|---|---|---|---|---|
| Changsha | 55.5 | 143 | 31 | 3.5 to 4.5 | 120 to 140 | 60 to 80 | 70 to 138 | 1999 |
| Bamei | 53.0 | 124 | 35 | 5.0 to 5.5 | 183 | 46 | 92 to 100 | 2003 |
| Datan | 65.4 | 150 | 62 | 7.0 | — | — | — | 2002 |
| Luguhe | 69.0 | 187 | 64 | 7.0 | — | — | — | 2004 |
| Shalaohe | 63.7 | 185 | 57 | 4.0 to 4.5 | 107 | 72 | 100 to 130 | 2001 |
| Longshou | 80 | 141 | 208 | 3 to 4.5 | 58 to 96 | 109 to 113 | 45 to 60 | 2001 |
| Qingxi | 52 | — | 150 | 5.0 | 120 to 150 | 52 to 64 | 90 to 100 | 1993 |

Note: 1 m = 3.28 ft, 1 $m^3$ = 1.31 $yd^3$, 1 $kg/m^3$ = 1.69 $lb/yd^3$

reasons. As a result, the cracking resistance of mass concrete is increased and temperature-control measures can be minimized. Therefore, MgO concrete is especially suited to construction of dams. This has been demonstrated by its application with no deleterious effects in several dams over the past three decades.

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