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Gypsum in construction: origin and properties

JOSEPH KARNI*, E'YAL KARNI†

* *Faculty of Civil Engineering,* † *Faculty of Architecture and Town Planning, Technion-Israel Institute of Technology, Technion City, 32000 Haifa, Israel*

Calcium sulfate, commonly known as natural gypsum, is found in nature in different forms, mainly as the dihydrate ($CaSO_4 \cdot 2H_2O$) and anhydrite ($CaSO_4$). They are products of partial or total evaporation of inland seas and lakes. Both the dihydrate and the anhydrite occur in nature in a variety of forms. The origin of gypsum, its genesis, varieties and properties are discussed, and the focus is then on the most common binding material produced from it, plaster of Paris (β-hemihydrate), known in France as 'plâtre de Paris', in the USA as 'calcined gypsum', and in Germany as 'Stuckgips'. Details are given of the properties of gypsum paste (setting, expansion, and adhesion) and of hardened gypsum (strength, bulk weight, thermal expansion, volume and linear changes under humidity fluctuations, moisture absorption, paintability, corrosivity, thermal and acoustic insulation behaviour, and fire resistance).

1. GENERAL

Naturally occurring calcium sulfate can be termed, in general, natural gypsum. It occurs in several forms, most common among which are the dihydrate ($CaSO_4 \cdot 2H_2O$) and anhydrite ($CaSO_4$). The chemical composition of the pure dihydrate, expressed by weight as oxides, is CaO 32.5%; SO_3 46.6%; H_2O 20.9%. Its bulk weight is about 2300 kg m^{-3}, its hardness 1.5–2.0 on the Mohs scale, and its colour is white or colourless. Commercial dihydrate minerals only rarely reach this purity. They usually contain varying amounts of clay, slate, anhydrite, chalk, dolomite, silica and iron compounds, as well as water. Depending on the specific impurities present, their colour may be grey, brown, red or pink. Their average mineralogical and chemical compositions, according to Schwiete and Knauf [1], are as given in Table 1. The chemical composition of pure anhydrite, expressed by weight as oxides, is CaO 41.2%; SO_3 58.8%. Its bulk weight is about 3000 kg m^{-3}, its hardness 3.0–3.5 on the Mohs scale, and its colour is white. Depending on the specific impurities present, the impure mineral may be grey, blue, red or brown in pale shades.

2. GENESIS

Partial or total evaporation of inland seas and salt lakes during various geological periods led to the formation of different crystalline minerals. Two of these are gypsum and anhydrite, which can be mined in rock form. According to Posnjak [2], the relative amounts formed of these two varieties were influenced by the conditions prevailing during the geological periods in question. For example, at a temperature of 30°C, as the salt concentration had increased 3.35–4.80 times its normal level in sea water, the calcium sulfate precipitated as anhydrite (see Fig. 1). The process may be summarized as follows. As evaporation proceeds, the minerals accumulate on the bottom in inverse proportion to their solubilities. The precipitation pattern is governed by chemical-physical principles, which in turn are affected by the geological evolution of the water body. This is the *chemical-physical* approach.

Another way of determining whether gypsum or anhydrite was formed first is provided by the *geological* approach. According to Antolini [3], the actual deposition sequence is determined by local conditions. It should be borne in mind that anhydrite may convert into gypsum, and vice versa, depending on the geological history of the formation. Thus there is no scope for generalization. In the calcium sulfate strata, formed as a result of sea water evaporation, gypsum and anhydrite appear side by side (horizontally or vertically), and occasionally as a mixture.

Differentiation between the two rocks is crucial for the gypsum industry. For plaster of Paris manufacture, for example, the purity of the dihydrate is of prime importance: a maximum dihydrate content is desirable, since the presence of anhydrite may actually jeopardize the production process or impair the quality of the product. In some cases, depending on the desired product, a certain percentage of anhydrite may even be beneficial. For certain products, such as ceramic gypsum or mould gypsum, an impurity level exceeding 1% (including anhydrite) is prohibitive. Gypsum deposits may occur as a result of volcanic activity, manifested as an accumulation of sulfuric acid (produced from sulfide minerals, such as pyrite), which converts calcium carbonate into calcium sulfate. This kind of gypsum, encountered in the form of nodules, is less exploitable than the evaporation deposits.

As well as the rock deposits, there are calcium sulfate sand dunes, formed through weathering of gypsum rock, and a soft mixture of gypsum and clay (gypsite), apparently the result of recrystallization of gypsum by separation from nearby deposits. Other, less frequent, varieties of dihydrate are: *alabaster*, a compact and

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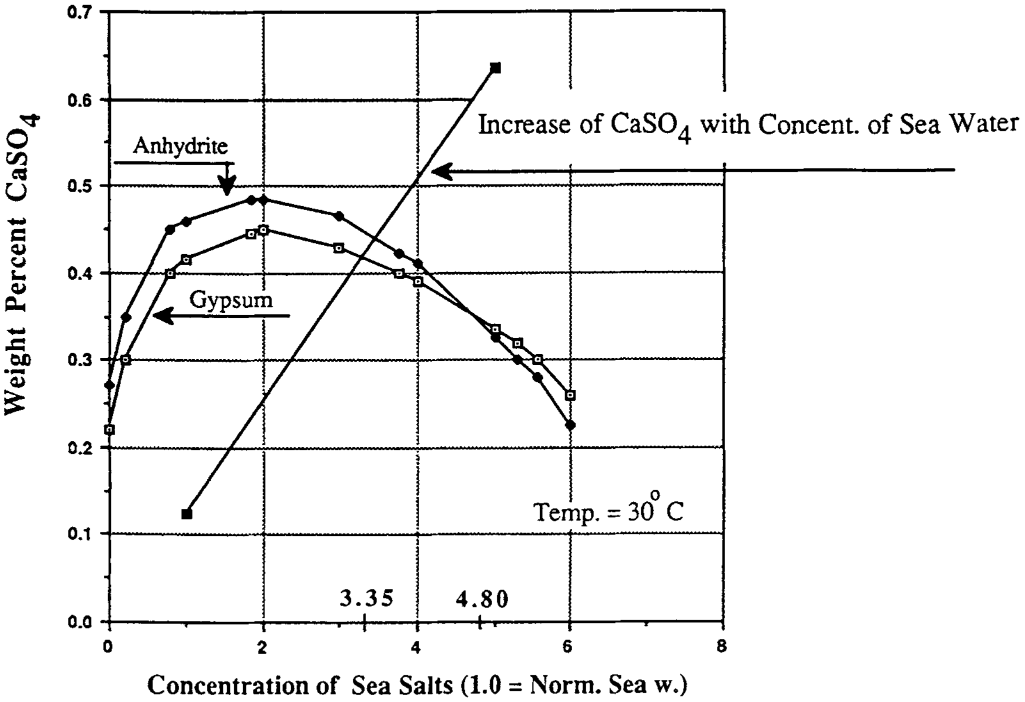

Fig. 1 Solubility curves for gypsum and anhydrite in solutions of sea water salts [2].

Table 1 Commercial dihydrate [1] composition in wt%

Mineralogical composition		Chemical composition	
Humidity (in 100°C)[a]	0.52	Humidity	0.52
$CaSO_4 \cdot 2H_2O$	90.20	Crystall. H_2O	18.88
Anhydrite	1.60	CaO	31.55
Calcite	0.73	SO_3	42.85
Dolomite	3.94	MgO	0.86
Unspec. impurities	3.01	CO_2	2.33
(quartz, clay, etc.)		$Fe_2O_3 + Al_2O_3$	0.52
		SiO_2 and others	2.49

[a] Max. temperature for moisture content determination of dihydrate is 60°C, but in [1] it says 100°C.

massive, marble-like material with a very fine crystalline structure used since antiquity for statuary and since the Middle Ages for interior decoration; *selenite*, a transparent crystalline material, used in antiquity for window panes; *satin spar*, a satin-like fibrous material, also occasionally used for decoration; *copy*, an efflorescence-like material, found on saline deposits in Australia; and *chemical gypsum*, a commercial by-product, mainly of the phosphate industry. Anhydrite also has several varieties, but these are of little importance compared with dihydrate.

3. CEMENTITIOUS MATERIALS PRODUCED FROM DIHYDRATE

We shall deal here exclusively with dihydrate. Cementitious materials in the building industry are based on calcium compounds, the most common ones being gypsum, air-hardening and hydraulic lime, natural cements, different kinds of Portland cement and some specialized cements. In Israel, air-hardening lime, plaster of Paris, and Portland cement are used. The principal feature of these cementitious materials is their tendency to harden on being mixed with water. They are also capable of adhesion and bonding and are used in the form of *paste* (with water only), *mortar* (paste plus fine aggregate) and *concrete* (paste plus fine and coarse aggregates). The calcium-based cementitious materials are classified as air-hardening and hydraulic. The air-hardening materials harden and subsist in air, but not in water. Air hardening lime as well as gypsum belong to this category; they harden by simultaneous drying and chemical reaction. Gypsum hardens in water, but it is also soluble in water, so that it lacks durability in an aqueous environment. Hydraulic cementitious materials harden and subsist both in air and water. Their hardening does not result from drying, but from chemical processes only.

Plaster of Paris belongs to the most ancient cementitious materials, dating back to the pyramid of Khufu, 5000 years ago. The ancient Egyptians used it both as coarse mortar and as plaster, and also to prepare interior surfaces for painting. For this application, the material has the advantage of being chemically neutral and thus compatible with paint. In fact, some of these paintings have survived in good condition to this day.

In medieval Europe, plaster of Paris served as a building material for palaces (e.g., in Germany). At present, its use is widespread in the US, in Europe and elsewhere, but not yet so in Israel. The source for this kind of cementitious material is *gypsum stone* ('natural gypsum', $CaSO_4 \cdot 2H_2O$), occurring in nature as rocks. It is relatively easy to mine the gypsum stone because of its low hardness. Mining is performed both subterraneously and in open quarries, the extracted stones being broken by automatic crushers. The material is then milled and ground to a powder, mostly before calcining, though occasionally calcining may precede grinding. (This ancient thermal processing of the raw material is responsible for the name 'gypsum': the Greek 'gupsos' derives from the two words denoting 'earth' and 'cooking'.)

Different types of cementitious material can be produced from gypsum stone. The only product used at present in Israel is plaster of Paris (hemihydrate or semihydrate). Its chemical formula is $CaSO_4 \cdot \frac{1}{2}H_2O$. Israeli Standard 198 [4] deals with cementitious materials obtained by partial dehydration of natural gypsum rock. The cementitious materials are: *structural hemihydrate* (predominantly $CaSO_4 \cdot \frac{1}{2}H_2O$), without setting retarder, and *structural retarded hemihydrate* (the former with added setting retarder).

The hemihydrate occurs in two forms: β and α. The β product is obtained by partial dehydration of the gypsum rock at 150–165°C. This is a very low temperature compared with that required for lime (about 1,200°C) or Portland cement (about 1,450°C). Calcining takes place in kettles (the most common variant) or in rotary kilns fired with coal, liquid fuel or gas. The hot combustion gases pass around the tank containing the powdered gypsum. The duration of calcining depends, of course, on the extent of combustion, but is normally 2–3 hours.

The α product is obtained by calcining of gypsum in an autoclave using high pressure steam. Calcining proceeds in the presence of water and a small amount of organic matter. The crystalline structure and the mechanical properties of the resulting product differ from those obtained by conventional calcining. In actual use, a smaller amount of water is needed to form a plastic paste which yields a stronger and harder product. The α gypsum serves for special purposes, for example, for making structural elements, but α gypsum is not dealt with here.

4. PLASTER OF PARIS, β-HEMIHYDRATE

4.1 General

As is well known, gypsum is an air-hardening cementitious material. It is capable of crystallizing and hardening in water as well, but does not subsist in water due to its solubility. When not exposed permanently to water, it is more durable, as is evidenced by extensive experience. Prolonged exposure to the atmosphere causes softening of the hemihydrate, and water flowing on its surface may dissolve and wash away the material. This is the reason why gypsum is recommended for indoor applications only. It can, however, be used in external walls if the process includes treatment with silicone or bitumen and if a plaster coating is added.

4.2 Properties of gypsum paste [5, 6]

4.2.1 *Gypsum chemistry*

Shortly after mixing plaster of Paris with water, setting begins, dihydrate ($CaSO_4 \cdot 2H_2O$) is formed, and the material hardens. This is also true for the retarded hemihydrate: as soon as setting has begun, the reaction proceeds rapidly, and the entire mass is converted into gypsum. According to Himsworth [7], calcium sulfate exists in three hydration states: *Anhydrite*, which contains no water of crystallization; *Gypsum*, which contains two water molecules; and *Hemihydrate*, which contains less water than the gypsum. The general formula of the compound is $CaSO_4 \cdot mH_2O$, where the value of m ranges from 0 to $\frac{2}{3}$. In industrial plaster of Paris, m is normally about $\frac{1}{2}$. At this water content, those properties that depend on m are stabilized and therefore the material is calcined to obtain a compound quite close to $CaSO_4 \cdot \frac{1}{2}H_2O$. When stored in humid air, the value of m increases and approaches $\frac{2}{3}$. On mixing with water, absorption is rapid up to $m = \frac{2}{3}$, further absorption taking place at a slower rate until dihydrate is formed. During the mixing process, the temperature rises to a constant value, but later it increases again. The first temperature rise is associated with the formation of $CaSO_4 \cdot \frac{2}{3}H_2O$, and the second with the formation of dihydrate.

4.2.2 *Setting*

The setting mechanism is explained by Le Chatellier's law. The hemihydrate dissolves in water, forming Ca^{2+} and SO_4^{2-} which with water form dihydrate that precipitates from the solution. The process continues until all the gypsum has passed the following three stages: 1, dissolution; 2, hydration, i.e., binding to the water; and 3, precipitation of the $CaSO_4 \cdot 2H_2O$ crystals. The setting rate of plaster of Paris depends on its fineness, purity and mixing velocity. To ensure convenient application, the time period from preparation of the low viscosity paste until it reaches a substantial viscosity must be long enough to allow casting of the gypsum, or making plaster out of it. Thus costly work with very small batches is avoided. To prolong the working time, retarders are added to the hemihydrate to obtain 'retarded plaster of Paris'. After setting has started in this material, it proceeds very rapidly until the entire mass has been converted into gypsum. Since completion of hydration of calcium sulfate is rapid in hemihydrate, wet finishing of the products is not required.

4.2.3 *Expansion of the paste*

On casting plaster of Paris, there is an initial volume contraction. In rapid setting material this contraction is barely noticeable, whereas in retarded hemihydrate the linear contraction reaches 0.05% (i.e., a volume reduction of about 0.15%). Contraction stops with the commencement of setting, when hydration has occurred in only a small portion of the material, and then expansion sets in. Initially, expansion is extensive, but it gradually slows down and stops after one or two days. The overall amount of linear expansion differs for the various types of gypsum: it ranges from 1% or more in high expansion (unretarded) plaster of Paris to 0.1% or less in low expansion (retarded) hemihydrate or in a material containing an expansion preventing additive. Thus, the increase in volume may amount to 3% or more. This property constitutes an advantage when gypsum is cast, since it ensures accurate dimensions and shape of the product. When gypsum serves as coarse mortar, interface cracks are avoided, in contrast to lime-cement mortar or cement mortar. As expansion continues even after the initially hot mass has cooled down to ambient temperature, it must be concluded that it is not caused by the heat evolved during setting. Neither is the volume increase a result of the chemical reaction:

$$\mathrm{CaSO_4 \cdot \tfrac{2}{3}H_2O + \tfrac{4}{3}H_2O = CaSO_4 \cdot 2H_2O},$$

because this reaction causes a volume *reduction* of 4%. It appears that expansion should be attributed to the forces arising during the growth of gypsum crystals and the geometric ordering of the growing crystals. Until the mass becomes rigid, the crystals can grow freely, while the formation of a rigid structure restrains the motions of their ends so that expansion takes place. The following factors affect the magnitude of expansion: 1, the fineness of the powder; 2, the water/gypsum ratio (ratio of mixture water to weight of gypsum); 3, added retarders or accelerators; 4, added sand; and 5, added lime paste.

4.2.4 *Effect of powder fineness*

It was found that, even for a constant water/gypsum ratio, the expansion of fine plaster of Paris was greater than that of coarse material.

4.2.5 *Effect of water/gypsum ratio*

Increasing the water/gypsum ratio reduces expansion. The reason for this is that the distances between particles increase with increasing water/gypsum ratio and, consequently, the crystals will have more space for growth. In addition, more water means a longer setting time, and a higher degree of hydration will be required to obtain a rigid mass, so that the growth rate will be lower after setting.

4.2.6 *Effect of retarders*

In the USA and the UK it is customary to add to plaster of Paris 0.1% keratin (a protein compound derived from horns and hoofs) as a retarder. Other retarders cited in the literature include gelatin, protein hydrolysate, lime, etc. A large number of materials, in different concentrations, have been tested at the Building Research Station in Haifa to determine the optimum processing time that would not impair the main properties of gypsum. The materials tested were: a common household detergent ('Ama'), lime, Teepol, gelatin, gelatinous hot wood adhesive, casein-base cold wood adhesive, Lissapol, 'skiza' resin, borax, casein and casein hydrolysate ('caseolysate') [5].

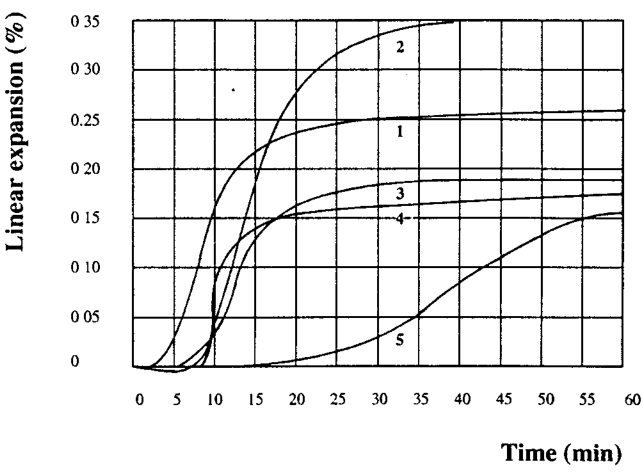

Fig. 2 Linear expansion of plaster of Paris having standard consistency [5]: 1, unretarded plaster of standard consistency, water/gypsum ratio = 0.56; 2, high-expansion plaster acc. to Andrews [8]; 3, unretarded plaster; water/gypsum ratio = 0.60; 4, retarded plaster of standard consistency, 0.1% caseolysate; and 5, retarded plaster of standard consistency, 0.8% gelatin.

It has been found that added retardants (as well as accelerators) usually reduce expansion during setting. This is due to the specific shape of the crystals formed in their presence. Retardants normally cause the formation of short and thick crystals, which fill more easily the spaces in which they grow. Under these circumstances, smaller forces develop in the bulk. The use of accelerators results in a larger number of small crystals than in pure water, so that here too the crystals are shorter. This explains the decreased expansion caused by the crystals in both cases. Fig. 2 shows the differences in linear expansion between retarded, unretarded and high-expansion plaster of Paris.

4.2.7 *Effect of added sand*

Sand added to plaster of Paris reduces expansion. For example, adding 5 parts of sand to one part of hemihydrate (by volume) reduces expansion to about 50% of the value for pure plaster of Paris. Find sand allows greater expansion than coarse sand.

4.2.8 *Effect of added lime paste*

In some countries slaked lime has been added to plaster both as a setting retardant and as an expansion reducer. Since lime paste is a strongly contracting cementitious material it reduces considerably the expansion of plaster of Paris. A 1:1 mixture, showing practically no expansion changes the nature of the set plaster. As regards setting, slaked lime is a poor retarder: a large amount of it would be needed and the product would be quite weak.

Therefore, slaked lime should not be used for this purpose, though addition of a certain amount may improve workability. Occasionally, plaster of Paris is added to lime plaster in order to accelerate setting and hardening; a typical amount is 10% of the dry mixture. It should be noted that addition of lime does not inhibit the chemical reaction between gypsum and water appreciably, though it may retard setting. This would impair the quality of the cementitious material, since the plaster–lime mixture can be remixed easily even after the plaster has become dihydrate, i.e., it has ceased to be a cementitious material. Working the gypsum–plaster mixture after the chemical process has advanced will markedly reduce the strength of the plaster. Therefore, a gypsum–lime mixture should not be used after thickening and it should not be remixed. For this reason, excessive working of the upper plaster layer, i.e., the finish layer, should be avoided.

4.2.9 *Adhesion*

Gypsum adheres well to different materials, including reed, wood chips, sawdust, sand, asbestos fibres, sisal fibres, etc. Fresh gypsum also adheres well to thoroughly hardened gypsum, yielding strong, monolithic products.

4.3 Properties of hardened gypsum

4.3.1 *Strength*

The strength derives directly from crystallization of the gypsum. Growth and interlocking of the contacting crystals impart strength to the gypsum paste. Strength is determined by the following factors: 1, the quality of the cementitious material (gypsum and additives); 2, the water/gypsum ratio; 3, the age of the product; and 4, the conditions of storage of the product, both *during strengthening* (of interest to the industry), and *after the strengthening period* (of interest to the user).

4.3.2 *Effect of quality of cementitious material*

The quality of the gypsum depends on the raw material composition, the calcining temperature, the particle fineness and the age of the cementitious material. These subjects have been discussed above. Table 2 shows how the quality of the added retardants affects the strength of plaster of Paris at the age of 14 days [5]. The best results were obtained with 'caseolysate' (casein hydrolysate). It was found that all the added retardants caused weakening of the hemihydrate. The extent of weakening depends on the type of retardant, the amount added and, occasionally, the water/gypsum ratio. Table 3 shows the effect of added slaked lime on the strength of plaster of Paris.

4.3.3 *Effect of water/gypsum ratio on strength*

The strength of gypsum depends largely on its water/gypsum ratio, decreasing with increasing water content. Therefore, high strength is achieved by adding to the gypsum only the amount of water needed for setting and crystallization (17 wt %). However, this amount is much smaller than that required to reach the desired plastic consistency and, consequently, a higher water/gypsum ratio is normally used. A typical value for manual compacting is 0.60. Table 4 shows the effect of the water/gypsum ratio on the strength of retarded and unretarded gypsum as a function of the environmental conditions.

4.3.4 *Effect of product age*

Strength increases with time. Israeli experience shows that under normal (ambient) finishing conditions, maximum strength is reached within 14 days in summer and within 28 days in winter. Table 5 illustrates the effect of age on the strength of plaster of Paris.

4.3.5 *Effect of conditions during strengthening*

Different conditions during the strengthening period will yield products having different strengths. These effects are studied by compression loading of specimens of retarded gypsum that had been treated as follows (Table 6 gives the compressive strength values for the gypsum): (1) drying under ambient conditions (27.5°C/73% RH);

Table 2 Compressive strength and tensile strength of retarded plaster of Paris [5][a]

Retardant and amount	Water/gypsum ratio[b]	Bulk weight (kg m^{-3})	Compressive strength		Tensile strength	
			(N mm^{-2})	% ch.[c]	(N mm^{-2})	% ch.[c]
Unretarded gypsum	0.63	1200	12.0	0	1.9	0
Caseolys. 0.2%	0.57	1290	11.3	−5.8	1.9	+1.6
Gelatin 0.85%	0.70	1120	7.3	−39.2	1.3	−29.2
Hot wood glue, 1.0%	0.66	1170	8.3	−30.6	1.8	−2.1
Protein hydrolys. 5.3%	0.56	1250	9.0	−25.2	1.1	−36.7

[a] Conditioning for 13 days at room temperature + one day in an oven at 50°C; duration of initial setting 20 ± 2 min.

[b] Water/gypsum ratio as required to obtain a paste of standard consistency.

[c] Change in strength is given relative to unretarded gypsum.

Table 3 Compressive strength and tensile strength of lime-retarded plaster of Paris [5][a]

Mixture	Water/gypsum ratio	Bulk weight (kg m^{-3})	Compressive strength (N mm^{-2})	Compressive strength % ch.[b]	Tensile strength (N mm^{-2})	Tensile strength % ch.[b]
Gypsum no lime	0.57[c]	1230	20.7	0	2.2	0
Gypsum + slaked lime, 5 wt %	0.63[c]	1150	14.5	−30.0	1.8	−18.2
Gypsum + slaked lime, 7.5 wt %	0.63	1140	14.0	−32.4	1.4	−35.8
Gypsum + slaked lime, 10.0 wt %	0.63	1130	13.2	−36.6	1.5	−31.7

[a] Conditioning: 13 days at room temperature + one day in an oven at 50°C.
[b] Water/gypsum ratio as required to obtain standard consistency.
[c] Change is given relative to gypsum without added lime.

Table 4 Effect of water/gypsum ratio on the strength of hardened gypsum [5]

Water/gypsum ratio	Retarded gypsum							Unret. gypsum
	Bulk weight (kg m^{-3})	Compr. strength (N mm^{-2})	Bulk weight (kg m^{-3})	Compr. strength (N mm^{-2})	Bulk weight (kg m^{-3})	Compr. strength (N mm^{-2})	Tensile strength (N mm^{-2})	Compr. strength (N mm^{-2})
	Conditioning before testing[a]							
	I	I	I	I	II	II	II	II
	Testing after (days)							
	7	7	28	28	14	14	14	14
0.50	1430	7.1	1400	10.4	1410	14.6	2.5	15.8
0.55	1270	4.6	1230	8.0	1300	13.0	2.0	14.0
0.60	1250	3.2	1170	5.1	1230	11.4	1.6	12.0
0.65	1190	2.5	1110	4.5	1170	10.8	1.3	
0.70	1140	2.2	1010	4.3	1130			
0.75	1070	1.5	1050	3.8	1040	9.5	1.2	

[a] Conditioning: I, drying at room temperature; II, drying at room temperature + one day in an oven at 50°C.

Table 5 Increase in strength (N mm^{-2}) of unretarded gypsum with time (water/gypsum ratio = 0.68) [5]

	Age (days)		
	1	7	28
In compression	2.7	3.2	7.5
In tension	0.7	1.2	1.4

(2) keeping in a humidity chamber (≥90% RH, temp. ?); (3) keeping in water (temp. ?); (4) drying at room temperature (27.5°C/73% RH) and finally conditioning for 24 h at 50°C; (5) drying at room temperature (27.5°C/73% RH) 6 or 9 days, then one day at 50°C and finally a few days in room conditions (27.5°C/73% RH); and (6) keeping 14 days in a humidity chamber and returning for a few days to room conditions (27.5°C/73% RH).

From the results in Table 6 it may be concluded that during the strengthening period the strength is influenced by the environmental conditions. It was found that: (a) the initial strength of specimens kept in water or in a humidity chamber was relatively high, but it decreased with time; (b) specimens kept for 14 days in a humidity chamber and then for a few days under ambient conditions showed higher strength than specimens kept in a humidity chamber during the entire conditioning period (specimens kept at 50°C on the last day were even stronger); (c) air-dried specimens reached maximum strength after about 14 days; and (d) specimens that had been air-dried and then kept for 24 h at 50°C showed even better results.

4.3.6 *Effect of conditioning of hardened product on its strength*

Since gypsum is hygroscopic, it is important to know the effect of environmental humidity on its strength. Table 7 shows the influence of humidity or moisture on hardened products of plaster of Paris based on a water/gypsum ratio of 0.60 (age ?).

The oven-dried product showed the highest strength. The 'dried strength' is an appropriate criterion for a

Table 6 Compressive strength (N mm^{-2}) of hardened gypsum as a function of conditioning (see text) during strengthening [5]

Condition	Compressive strength (N mm^{-2})												
	Specimen age (days) 1	3	7	8	9	10	12	13	14	17	21	24	28
(1)	3.0	2.9	4.6						7.4				6.4
(2)	3.3	3.4	3.2						2.3				3.1
(3)	2.9	3.1	2.5						2.1				1.8
(4)									8.5				7.9
(5)				4.5[a]	5.8[a]	6.3[a]	6.3[b]	7.5[b]	6.4[b]				
(6)										3.5	6.0	6.7	6.7 8.3[c]

[a] 6 days drying at room temperature.
[b] 9 days drying at room temperature.
[c] kept at 50°C on the last day.

Table 7 Effect of humidity or moisture on the strength of hardened products of plaster of Paris [8]

Conditioning	Moisture in gypsum (%)	Compressive strength	
		(N mm^{-2})	%
Dried at 35–40°C	0	13.8	100.0
In air of 65% RH	0.04	13.6	98.5
In air of 90% RH	0.15	12.9	93.5
With 1% water added	1.00	7.7	56.0
With 3% water added	3.00	7.1	51.5
Immersed in water	17.50	6.4	46.5

comparison of gypsum from different sources for uses where moisture absorption is not possible. It was found that the strength of hardened gypsum decreases as a result of moisture absorption. If moisture can be absorbed, it is necessary to assume a reduced strength, as seen from Table 7. It was also found that, under moisture conditions common in residential buildings, there is no significant effect, particularly since dried gypsum is capable of regaining strength.

4.3.7 *Enhancing strength by use of fibres and polymers*

A research project on the improvement of gypsum by the use of fibres and polymers [9] was completed at the Building Research Station in Israel in 1976. The work was aimed at improving the strength of thin gypsum slabs designed for the assembly of light partitions and for 'dry plaster'. Local gypsum, satisfying the requirements of Israeli Standard 198, was used to prepare the specimens. The fibres were chopped glass fibres, 12 mm long and 10 µm in diameter, made from E glass rovings (Type 8252P-2380). The following polymers were tested: polyvinyl acetate emulsion 'Servinyl 1040P' and acrylic copolymer emulsion 'Seracryls 4000'. Tap water was used. The consistency of the gypsum paste was uniformly liquid and suitable for manual compacting. The quality of the hardened composite, made from gypsum with added fibres and polymer, was established by determining its flexural and compressive strength and comparing these values with those for uncompounded material and those of gypsum containing polymer only or chopped glass fibres only. Some results of this work are given in Table 8.

The following conclusions may be drawn. 1, The compressive and flexural strength of gypsum can be

Table 8 Relative composite strength (%) [9]: A, 'Servinyl 1040P'; B, 'Seracryls 4000'; glass fibres 12 mm long

Strength	Composite						
	Plaster of Paris	Plaster of Paris + polymer		Plaster of Paris + fibres		Plaster of Paris + polymers + fibres	
		A	B	A	B	A	B
Bending strength prisms 40 mm × 40 mm × 160 mm	100	128	106	142	145	186	172
Bending strength panels 300 mm × 400 mm × 10 mm	100	137	131	175	173	241	202
Compressive strength prism-halves 40 mm × 40 mm	100	135	113	96	98	116	107

improved by the addition of a suitable polymer. 2, Adding chopped glass fibres to gypsum can improve its flexural strength considerably; however, its compressive strength does not increase and may even decrease to a certain extent. 3, The flexural strength of the composite can be improved quite considerably by adding both polymer and chopped glass fibres to the gypsum matrix. The effect is synergistic, i.e., the flexural strength improvement is quantitatively greater than the arithmetic sum of improvements obtained with the fibres and polymer separately. This is particularly conspicuous in the case of thin slabs. 4, It seems plausible that an additional study, based on fibres and polymers in different combinations, might lead to a further improvement of the matrix and the fibre–matrix adhesion and thus to a stronger composite as a whole. Removal of excess water from the plastic paste, while compacting the composite, might also improve strength as a result of the increased density as well as the decreased water/gypsum ratio in the gypsum.

4.3.8 *Thermal expansion*

Products of plaster of Paris expand on heating. The linear thermal expansion coefficient of the hardened gypsum is 20×10^{-6} K^{-1}, i.e., about twice that of concrete.

4.3.9 *Volume changes and linear changes due to changes in moisture*

Gypsum products contract on drying to a limited extent. The linear change does not exceed 0.01% (ordinary concrete contracts 0.03–0.08%). It can thus be concluded that hardened gypsum does not undergo any appreciable volume change as a result of moisture changes.

4.3.10 *Moisture absorption*

Gypsum (not painted) is capable of absorbing and releasing excess moisture in an apartment (condensation control), which may affect the quality of housing.

4.3.11 *Painting*

Gypsum can be painted with oil paint or plastic paint a few days after it has been prepared.

4.3.12 *Corrosion*

Metal may corrode in contact with gypsum during setting and hardening of the latter as well as during the service of gypsum products in a humid environment. Gypsum products should not be used under conditions of high humidity, owing to the effect on gypsum and the risk of metal corrosion. The safest way of preventing corrosion is to employ conventional methods of metal pretreatment. Even if corrosion does not cause structural damage, it may result in undesirable staining.

4.3.13 *Thermal insulation*

Generally speaking, the thermal insulation capability of gypsum is a direct consequence of its porous structure. To obtain a wall with high thermal insulation, one must usually accept a certain reduction in strength requirements. This can be done, since a wall is normally expected to carry only its own weight. The thermal conductivity of set plaster of Paris is approximately $\lambda = 0.6$ W m^{-1} K^{-1} and that of cellular gypsum is $\lambda = 0.2$ W m^{-1} K^{-1}. Thin gypsum boards do not substantially reduce the thermal conductivity of a wall, but when adjacent to an air space they can serve well as heat insulators. Improved insulation is achieved by using special boards or by adding insulating materials. Satisfactory solutions can be reached by appropriate combinations of the various materials (the external wall material, the gypsum board and the insulator) and intelligent design.

4.3.14 *Fire resistance*

Gypsum is a non-flammable material that can serve to protect both load-bearing and unloaded elements of steel and wood against fire. The fire resistance of gypsum products derives primarily from its content of water of crystallization, amounting to 17% of its weight. When gypsum is heated or calcined at relatively low temperature, its water of crystallization is gradually liberated as vapour, and the heat consumed in this reaction reduces the rate of temperature rise. In the case of fire near gypsum products, calcination of their exposed surfaces begins, penetrating slowly into the bulk of the gypsum. The progress of calcination is slowed down by the layer of calcined gypsum on the surface of the product, which adheres well to the underlying uncalcined gypsum. Retardation of the process becomes more efficient with increasing thickness of the calcined gypsum layer. The materials adjacent to the inside of the gypsum product reach temperatures not exceeding 150°C by the time calcination is completed. Since this temperature is much below the ignition temperatures of conventional building materials and most materials stored inside the buildings, the gypsum serves as a fire retardant. An additional contribution to localization of a fire stems from the limited contraction of gypsum on drying. Owing to the low bulk weight of the gypsum, heat transfer is reduced. Gypsum boards lined with cardboard of special paper are not flammable, though the cardboard carbonizes.

4.3.15 *Acoustic insulation*

Two properties are of significance in building acoustics: acoustic insulation and sound absorption. Acoustic insulation means the ability of an element (wall, partition, ceiling) to prevent or reduce the transfer of sound through that element. Sound absorption signifies the loss of energy of sound when making contact with the surface of the element. This effect depends mainly on the nature of the material surface. Products of plaster of Paris, having a relatively low bulk weight, are poor sound insulators compared with materials of higher bulk weight, but gypsum board partitions can be made quite sound-insulating. As regards sound absorption, regular plaster having a smooth surface is practically not absorbent. However, considerable sound absorption is shown by gypsum containing some special additives. This kind of plaster is rather soft and easily scratched, so that it is usually employed only for coating of ceilings and upper parts of walls.

REFERENCES

1. Schwiete, H. E. and Knauf, A. N., 'Alte u. neue Erk. u. Erz. u. Anw. der Gipse' (1963).
2. Posnjak, E., *Amer. J. Sci.* (1940).
3. Antolini, P., in Proceedings of the RILEM International Symposium on Calcium Sulfates and Derived Materials, Saint-Rémy-lès-Chevreuse, France, May 25–27, 1977.
4. Israeli Standard 198 (1993): Hemihydrate building gypsum.
5. Karni, J., 'Suggestions for the use of gypsum semihydrate in the local building industry' (in Hebrew), 'Researches', No. 4 (Building Research Station, Technion—Israel Institute of Technology, 1956).
6. Karni, Joseph. and Karni, E'yal., 'The Gypsum in Building' (in Hebrew) (Building Research Station, Technion—Israel Institute of Technology, 1987).
7. Himsworth, F. R., 'The Setting and Expansion of Plasters' (The Society of Chemical Industry, London, 1947).
8. Andrews, H., 'The effect of water contents on the strength of calcium sulphate plaster products', *J. Soc. chem. Ind.*, **65** (1946).
9. Karni, Joseph., 'Fibre-reinforced, polymer-modified Plaster of Paris', in RILEM International Symposia 'Calcium Sulfates and Derived Materials', edited by M. Murat and M. Poucault (1977).

RESUME

Le gypse dans la construction: son origine et ses propriétés

Le sulfate de calcium, généralement appelé gypse naturel, se trouve dans la nature sous différentes formes, souvent comme dihydrate ($CaSO_4 \cdot 2H_2O$) et comme anhydrite ($CaSO_4$), qui sont le résultat d'une évaporation totale ou partielle de mers intérieures et de lacs. Aussi bien l'anhydrite que le dihydrate existent dans la nature sous une variété de formes.

Après un compte-rendu sur l'origine du gypse, sa genèse, ses variétés et propriétés, l'article traite de la matière la plus couramment produite à partir du gypse, qui est connue en France sous le nom de 'plâtre de Paris' (β-semi-hydrate), aux USA sous celui de 'calcined gypsum', et en Allemagne sous celui de 'Stuckgips'.

L'article décrit aussi en détail les propriétés de la pâte de plâtre (prise, dilatation, adhérence) et celles du plâtre dur (résistance, poids, dilatation thermique, volume et changements linéaires sous l'influence des fluctuations de l'humidité, absorption d'eau, aptitude à être peint, corrosion, comportement à l'isolation thermique et acoustique et résistance au feu).