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Self-compacting gypsum based light-weight composite: theoretical and experimental study

Abstract

This article addresses experiments and theories of a novel self-compacting gypsum based light-weight composite (SGLC), wherein β-hemihydrate was used as binder and one light-weight material (0-2 mm) was used as aggregates. The mix of the new composite was designed based on packing theory applying the modified Andreasen and Andersen (A&A) grading line to achieve an optimal packing of all the applied solid materials. The effect of the distribution modulus (q) in the Andreasen and Andersen equation was investigated. The developed mix was studied from its both fresh and hardened state, including the flowability, density (porosity), and mechanical properties. The thermal physical properties of the new developed composite were investigated too. The study demonstrates a considerable improvement of the new composite from both thermal and mechanical properties compared to normal gypsum plasterboard.

Introduction

Gypsum plaster is one of the earliest building materials elaborated by mankind and its utilization history can be traced to 4000 years ago. Gypsum plasterboard, usually produced from β-hemihydrate, is used extensively for interior walls or ceilings due to its easy fabrication features, excellent fire resistance properties, environmental friendliness, aesthetics, low price, etc. A high amount of excess water is usually needed for the β-hemihydrate hydration to produce gypsum plasterboard, whereas the removal of the excess water during the curing period causes some conflicting consequences such as a great consumption of heat energy and a high porosity of the final gypsum /1/. It is demonstrated that the resulted low thermal conductivity contributes a slower heat transfer between the indoor and outdoor environment, which leads to a better indoor thermal comfort, as well as a good fire resistance. However, the resulted low strength causes not only a limitation of the application of the gypsum board but also a swift strength degradation during a fire, which then leads to a quick failure of the structure.
Numerous efforts were already spent to address this problem, for instance applying fibers such as glass fibers, carbon fibers, polyester fibers, and natural fibers to reinforce gypsum board. But these reinforcements have more or less disadvantages. Singh and Garg /2/ reported short chopped glass fibers could not contribute the strength improvement. Eve et al. /3, 4/ reported a reduction of Young's modulus and the strength of the gypsum composites when increasing the content of polyamide fibers and polypropylene fibers. Colak /5/ investigated the polymer of methylmethacrylate (MMA) reinforced plaster composites and reported no strength improvement was achieved at a low MMA content of until 10% by weight. Deng and Furuno /6/ reported that with a length of 12 mm and content of 12% by weight, polypropylene fibers reinforced gypsum particleboard (gypsum as a binder, and wood particles as the strengthening material) can achieve an optimal performance (physical and mechanical properties), but

such a high amount of fiber reinforcement cause a considerable cost increase and also mixing difficulties. Hernandez-Olivares et al. /7/ reported that short sisal fibers could not contribute to the fire resistance property of the reinforced gypsum board.
The present research aims at the development of a gypsum based light-weight composite. A light-weight aggregate (LWA) was used to achieve a good thermal property of the developed composite. The mortar mix was designed based on the packing theory applying the modified Andreasen and Andersen (A&A) grading line to obtain an optimal packing of all the applied solid materials, which then will lead to an optimal mechanical properties. The effect of the distribution modulus (q) in the Andreasen and Andersen equation was investigated. The developed mix was studied in both fresh and hardened states, including the flowability, density (porosity) and mechanical properties. The thermal physical properties of the new developed composite were investigated as well.

Mix design concept

One of the current gypsum plasterboard production characteristics is the self-compacting property, i.e., the generated gypsum can flow freely under its own weight into any shape, which will also be an important feature of the developed materials with the new mix design. Compared to the new concept of self-compacting gypsum based composite, self-compacting concrete (SCC) has been developed and studied for decades /8/. Brouwers and Radix /9/, and Hunger and Brouwers /10/ further improved the development of the SCC applying a particle size distribution (PSD) method, and they found that the PSD of all solids in their good performance should be in accordance with the modified grading line from Andreasen and Andersen /11/, reading

$$P(D) = \frac{D^q - D^q_{min}}{D^q_{max} - D^q_{min}} \tag{1}$$

where D is the particle size in the mix, D_{max} and D_{min} are the maximum and minimum particle sizes in the mix, respectively, and q is the distribution modulus.
Applying the PSD theory, the particles can be better packed, which results in improved hardened properties as well as an improved workability since more water is available to act as a lubricant between the particles. Hüsken and Brouwers /12/ developed a new mix design tool using this theory considering the entire size range. In this developed tool, the modified Andreasen and Andersen curve works as a target function for the subsequent granular optimization of the individual materials. The proportions of the individual materials in the mix design are adjusted until an optimum fit is reached with the target value, using an optimization algorithm based on a Least Squares Method (LSM), i.e. the deviation between target curve and composed mix expressed by the sum of the squares of the residuals (RSS) at defined particle sizes. This design method can be expressed using Fig. 1, and a detailed description can be found in /12/.

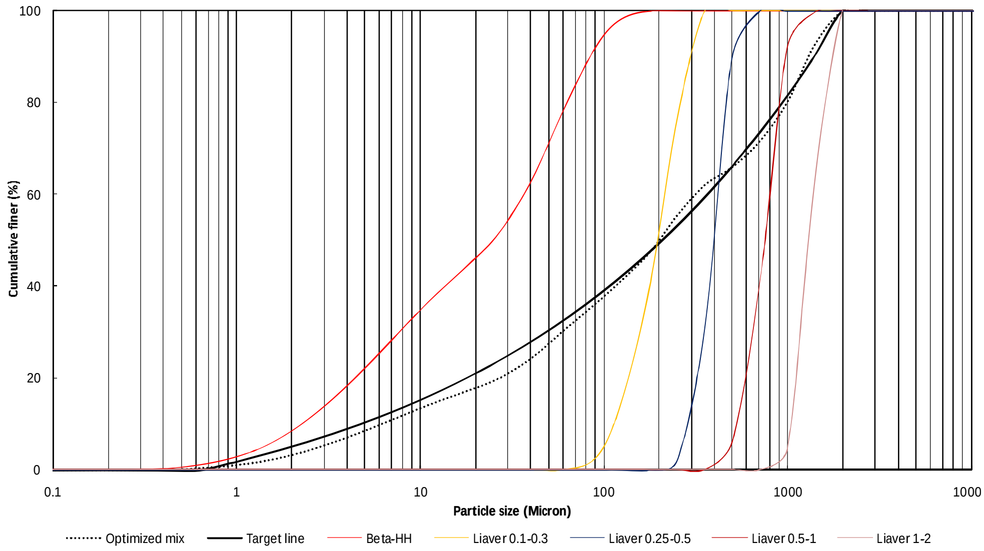

Fig. 1: The PSDs of the materials used in the mix design.

In this mix, β-hemihydrate was used as binder. The applied β-hemihydrate, produced from the flue gas desulfurization (FGD) gypsum, was provided by Knauf Gips KG (Germany). The X-ray diffraction (XRD) patterns shows that the β-hemihydrate almost entirely consists of $CaSO_4 \cdot 0.5H_2O$. The chemical analysis of the material carried out with energy-dispersive X-ray spectroscopy (EDX) is listed in Table 1. It is shown there are only very small impurities (Si, Mg and Al in total less than 3% by mass) in the sample, which also confirms the XRD result. The particle size distribution (PSD) was measured with Mastersizer 2000, and the result is shown in Fig. 1.

Element	wt.%	at.%	K-Ratio
O	48.86	67.84	0.0714
Mg	0.87	0.80	0.0030
Al	0.80	0.66	0.0037
Si	1.32	1.05	0.0082
S	21.46	14.87	0.1758
Ca	26.68	14.79	0.2285
Total	100.00	100.00	

Table 1. Chemical composition analysis from EDX.

The used light-weight aggregates here are produced from recycled expanded glass, which are closed hollow spherical particles. Different particle size groups of 0.1~0.3 mm, 0.25~0.5 mm, 0.5~1.0 mm, 1.0~2.0 mm were used in the present mix design (Fig. 1). The densities range from 0.35-0.81 g/cm^3 and the crushing resistance is over 3 N/mm^2. The chemical composition of them is listed in Table 2.
It is demonstrated that the paste content (defined as particles smaller than 125 μm) increases with the decrease of the distribution modulus /12/, which obviously affects the final properties of the developed mixture. Hunger and Brouwers /10/ recommended a range of $0.30 < q < 0.35$ for self-compacting concrete, while Hüsken and Brouwers /12/ suggested $0.35 < q < 0.40$ for earth-moist concrete (i.e. zero slump flow concrete). In

this study, the effect of the distribution modulus on the mechanical properties and thermal properties of the designed composite was investigated by using different values to find an optimal value.

Chemical composition	wt.%
SiO_2	71 ± 2
Al_2O_3	2 ± 0.3
Na_2O	3 ± 1
Fe_2O_3	0.5 ± 0.2
CaO	8 ± 2
MgO	2 ± 1
K_2O	1 ± 0.2
Trace	< 0.5

Table 2. Chemical composition of light-weight aggregates.

The water content affects significantly on both mechanical and thermal properties of the gypsum board, which was investigated in detail /1/ /13/. In the present study first the water demand was determined applying the mini-slump flow test. A detailed water demand test procedure and analysis can be found in Yu and Brouwers /1/ /14/. Several water/hemihydrate ratios were used in the mix design to try to achieve an optimal balance of both mechanical and thermal properties. A detailed analysis is presented elsewhere /15/. A special developed superplasticizer (SP) /16/ was applied to adjust the flow ability of the mixture to the desired value.

Material	Mix 1	Mix 2	Mix 3	Mix 4
Distribution modulus	0.20	0.25	0.30	0.35
β-hemihydrate (kg)	665.8	593.8	532.6	474.0
LWA 0.1-0.3mm (kg)	65.8	102.9	97.5	94.8
LWA 0.25-0.5mm (kg)	16.4	15.8	52.5	42.1
LWA 0.5-1.0mm (kg)	57.5	39.6	26.3	35.1
LWA 1.0-2.0mm (kg)	16.4	39.6	41.3	56.2
Water (kg)	429.4	385.9	372.8	355.5
SP/hemihydrate	0.2%	0.25%	0.3%	0.3%
Water/hemihydrate	0.60	0.65	0.70	0.75

Table 3. Dosages of the developed mixes (based on 1 m^3).

Table 3 shows four designed mixes applying different distribution moduli. Clearly we can see that the paste amount (here the β-hemihydrate) is increasing with a decrease of the distribution modulus.

The new composite in hardened state

The samples were cast using prisms with a size of 160 mm × 40 mm × 40 mm. After demoulding, the samples were cured at room temperature for 7 days, followed with a drying procedure in an oven at 40 °C until the mass is constant to remove the free moisture. All the tests were repeated three times, and in each time 6 samples were prepared with the same mix to assure the test results are representative.
The density is related strongly with the mechanical and thermal properties of gypsum board, which was studied in detail in Yu and Brouwers /1/ /13/. In the present study, the effect of the density on the new composite was studied as well. The density of the sample was calculated from its measured size and mass. Fig. 2 shows a relation between the calculated density and the applied distribution modulus. It is clear that the density was influenced significantly by the distribution modulus. The density reduces with the increase of the distribution modulus. This can be explained from the reduction of the paste amount when the distribution modulus increases, which leads to a decrease of the density of the composite due to the low density of the used aggregates.

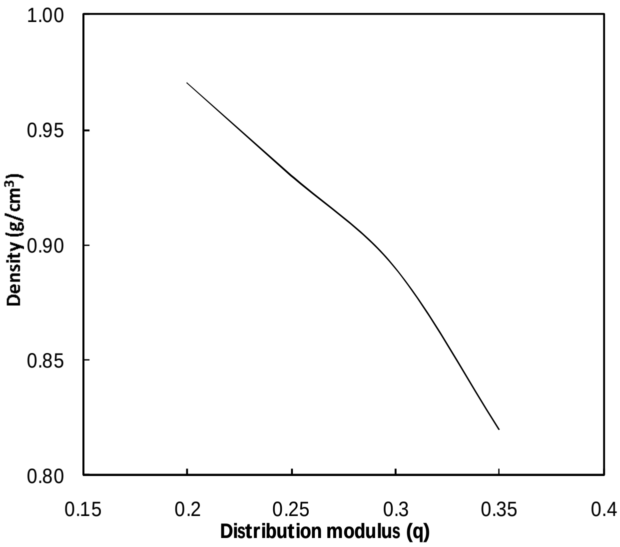

Fig. 2: The relation between the distribution modulus and the computed density.

The mechanical properties of the samples with the optimized mix design were investigated from its flexural and compressive strength. The flexural strength was measured with the three-point bending test following the standard EN 13279-2 /17/. A load was applied vertically by means of the loading roller to the opposite side face of the prism with a rate of (50 ± 10) N/s until fracture. The compressive strength was measured with the half prisms left from the flexural test on the molded side faces over an area of 40 mm × 40 mm with a load rate of (2400 ± 200) N/s until fracture.
The flexural strength is calculated from

$$\sigma_f = \frac{3F_{rupt}L_0}{2WH^2} \tag{2}$$

where F_{rupt} is the breaking load (N), L_0 the distance between the supports of the bending machine (mm), W (mm) and H (mm) the width and height of the samples, respectively.
The compressive strength is calculated from

$$\sigma_c = \frac{F_c}{1600mm^2} \tag{3}$$

where F_c is the maximum load at fracture (N).
The results of the strength versus the distribution modulus are shown in Figs. 3 and 4.

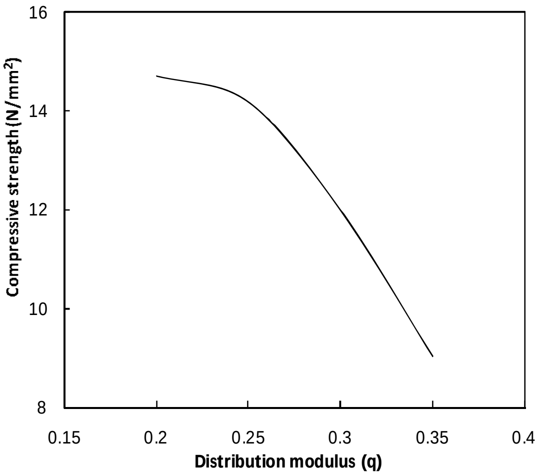

Fig. 3: The compressive strength versus the distribution modulus.

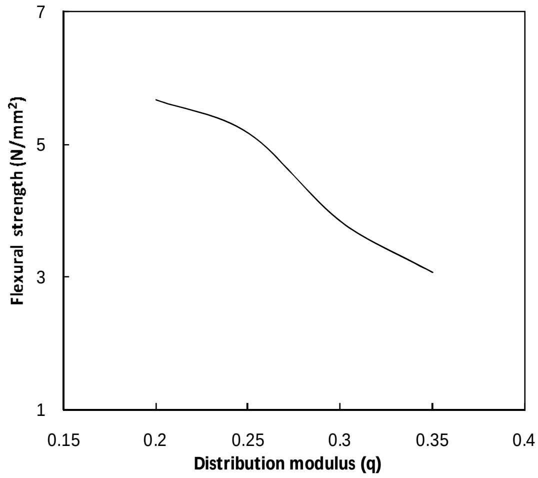

Fig. 4: The flexural strength versus the distribution modulus.

It is clearly demonstrated from Figs. 3 and 4 that the strength decreases as an increase of the distribution modulus. It shows that both the compressive and flexural strength decreases little when the distribution modulus increases from 0.20 to 0.25, however they decrease dramatically when the distribution modulus increased from 0.25 to 0.35. It is indicated that the strength is affected more at a relatively larger distribution modulus.
Here at a distribution modulus of 0.25, the flexural strength of the new composite is 5.2 N/mm^2 with a density of 0.93 g/cm^3. At this density the flexural strength of pure gypsum plasterboard is 3.1 N/mm^2 /1/, which means a 73.3% improvement of the strength was achieved by the developed composite.
This new composite is assumed to be used potentially as indoor wall board with a good thermal comfort. Hence the thermal conductivity was also addressed in this research. To achieve a good fire resistance of the new gypsum based wall board, it is important to obtain a low thermal conductivity as well. Therefore, as a very important thermal

property of a material that indicates its ability to conduct heat, thermal conductivity was investigated in detail here.

In the present study, the new developed composite was tested applying an ISOMET Model 2104 /18/. It applies a dynamic measurement method to measure the thermal conductivity. The measurement time is about 8-16 minutes /18/. For the thermal conductivity measurement, the sample was produced with a unified size of 200 × 150 × 20 mm^3. First again the effect of the distribution modulus on the thermal conductivity was studied. Fig. 5 shows the measured thermal conductivity versus the distribution modulus.

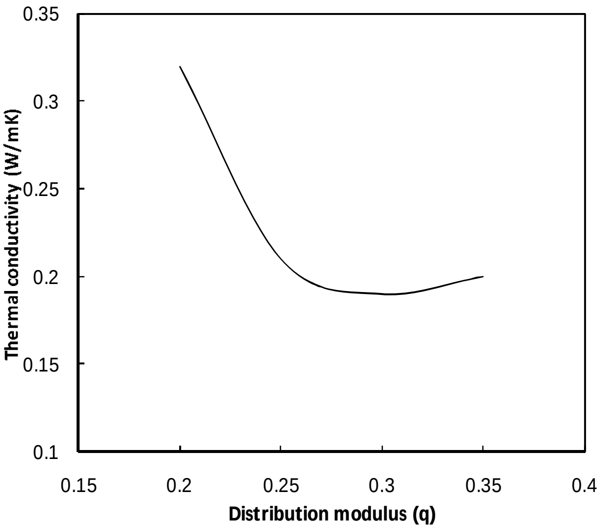

Fig. 5: The thermal conductivity versus the distribution modulus.

The thermal conductivity decreased as an increase of the distribution modulus from 0.20 to 0.25. Also it can be seen that the thermal conductivity remains quite stable when the distribution modulus varied from 0.25 to 0.35. At a distribution modulus of 0.25, the thermal conductivity is 0.20 W/(m·K). With a same density (i.e. 0.93 g/cm^3), the thermal conductivity of pure gypsum board is 0.28 W/(m·K), which indicates that an improvement of 28.6% is obtained with the new developed composite.

Conclusions

This study aims at the development of a novel self-compacting gypsum based light-weight composite that can be used as indoor wall board. A mix design tool developed for concrete was applied for the design of the new composite. And one type of light-weight aggregate was used in this composite. The following conclusions can be drawn:

1. The mix design concept is suitable for the design of the gypsum based composite;
2. The effect of the distribution modulus in this mix design equation was investigated and an optimal value of 0.25 was found;
3. A new type of superplasticizer was used for this new composite production and it showed a very good performance;
4. The hardened property (both the mechanical and thermal properties) of the new composite shows a significant improvement compared to traditional gypsum board.

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