SHRINKAGE CRACKING IN CELLULAR CONCRETE BLOCKS MASONRY UNITS

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ABSTRACT

The analysis of two groups of residential houses constructed with autoclaved aerated concrete (AAC) blocks with severe damages is described. Principal damages consist on cracks of various type and magnitude (diagonal, vertical, coincident with joints, across the blocks, etc.) The work developed had three parts: survey on site (damage survey, crack measurement, determination of shrinkage on walls, control of level changes on houses, sampling of soils and concrete blocks on remaining storing in place) laboratory testing of soils and AAC blocks (density, compression strength, flexural strength, shrinkage movements, absorption, etc.) and theoretical considerations. An additional analysis was made using Finite Element Method.

The causes of damages were founded to be a combination of expansive clays action (due to an inappropriate foundation design and its incompatibility with AAC blocks walls) and inadequate properties of AAC employed (low density, low strength and relatively high shrinkage changes of volume).

Key words: Block masonry / autoclaved aerated concrete / cellular concrete blocks / shrinkage cracking / deterioration.
INTRODUCTION

The analyzed case had the objective of determining the causes of diverse pathologies that were presented in two groups of residential houses. The construction system employed make use of autoclaved aerated concrete (AAC) blocks for walls and panels of the same material for roofing, while the foundation is a reinforced concrete double slab. As a very important fact it should be consigned that the soil of foundation is formed by active clays.

The pathologies consist basically on numerous vertical or slope cracks on walls that embraced all their thickness. On the other hand, another accessory constructions such as perimetal sidewalks, stonemasons, street sidewalks, etc. present frequent cracks, evident symptom of soil movements. The study approached the problem of present pathologies and their possible causes from two aspects: the floor-structure interaction and the physical-mechanical characteristics of the blocks material, that is AAC. Obviously both factors acted, in this case, concomitantly and in that way the analysis of the problem was made. However, the present work is limited to the analysis made about the properties of AAC.

TASKS DEVELOPMENT

Field activities and laboratory studies carried out to determine the caracteristicas of the concrete cellular employee in the walls are described.

Table 1. On-site measurements of length variations

<table>
<thead>
<tr>
<th>Poin identification</th>
<th>Measurement cross the crack</th>
<th>Dimensional variations (per thousands or mm/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1° (7 days)</td>
</tr>
<tr>
<td>1</td>
<td>Si</td>
<td>+0.160</td>
</tr>
<tr>
<td>2</td>
<td>No</td>
<td>+0.127</td>
</tr>
<tr>
<td>3</td>
<td>No</td>
<td>+0.137</td>
</tr>
<tr>
<td>4</td>
<td>Si</td>
<td>+0.139</td>
</tr>
<tr>
<td>5</td>
<td>No</td>
<td>+0.083</td>
</tr>
<tr>
<td>6</td>
<td>No</td>
<td>+0.032</td>
</tr>
<tr>
<td>7</td>
<td>No</td>
<td>+0.063</td>
</tr>
<tr>
<td>8</td>
<td>Si</td>
<td>+0.183</td>
</tr>
<tr>
<td>9</td>
<td>No</td>
<td>+0.097</td>
</tr>
<tr>
<td>10</td>
<td>Si</td>
<td>+0.100</td>
</tr>
<tr>
<td>11</td>
<td>No</td>
<td>+0.223</td>
</tr>
<tr>
<td>12</td>
<td>Si</td>
<td>+0.027</td>
</tr>
<tr>
<td>13</td>
<td>Si</td>
<td>+0.420</td>
</tr>
<tr>
<td>14</td>
<td>No</td>
<td>+0.056</td>
</tr>
</tbody>
</table>
Sampling of AAC blocks in storing

Due to problems appeared during the works, still before concluding the construction, it was decided to suspend the employment of this material type in the construction, and so there was an important number of unused blocks in a storing. From this storing was taked out a first sample of 24 blocks in so manner that, for their position inside the whole, were subjected to different conditions (sun, humidity, rain, etc.) and, at the same time, a bigger randomness in the election of the blocks were also guaranteed. In all cases two blocks for each sample in each one of the elected positions were taken, the samples extracted for their analysis in laboratory being identified.

Later, a suplementary sample consistent in two pieces of about 50 cm long was obtained from roofing panels (cut with abrasive disk, including its reinforcing steel rebars) and a second group of 17 12.5x25x50 cm blocks.

Once in laboratory, the blocks were cut in convenient forms to carry out the different tests, while for some types of studies complete blocks were used.

Placement of reference points for in-situ mesearument of dimensional variations

Reference points were placed in 3 houses in such a way of registering dimensional variations in healthy blocks and in cracked blocks. The dimensional variations in 14 couples of points were analyzed in this way. The measuring instrument was a length comparor that allows the detection of length variations with a precision of 0,001 mm, over a base length of 300 mm. The variation of the distance among reference points (small metallic disks firmly stuck to the surface of the walls) is indicated as fraction of the 300 mm reference longitude.

After an initial reading at reference points installation, there were carried out two readings of dimensional variations, registering in each opportunity the ambient temperature and relative humidity in order to define the hygrothermal conditions of each point. Results are showed in Table 1.

In this Table only a few values correspond to mensurations carried out on longitudes that don’t cross joints between blocks neither cracks, and thus their results can be used to evaluate the movements due exclusively to shrinkage. In the remaining cases, where the mensuration crosses a fissure, the result combines the effect of the retraction and that of the relative movement of the two sectors separated by the crack.

Laboratory testing

Density and moisture content of ACC

It was determined on 62 cubic specimens sawed from blocks, roomed in laboratory from 10 to 15 days, using Rilem LCS test method. Results were:
Average dry density: 508 kg/m³
Standard deviation: 29.0 kg/m³
Coefficient of variation: 5.7%
Inferior characteristic value (5% fractil): 471 kg/m³
Superior characteristic value (fractil 95%): 566 kg/m³
Average moisture content (dry weight basis): 11%

Density was also determined on complete blocks, in the condition as they were received in laboratory, obtaining the following values:

Average dry density: 680 kg/m³
Average moisture content (dry weight basis): 34%

**Water absorption and porosity of AAC**

It was determined on test tubes sawed from blocks, submerged in water until apparent saturation, using Rilem LC 6.1 test method. Results were:

Water absorption (mass basis): 77.2%
Water absorption (volume basis): 38.6%
Absolute density of solids: 2.4 g/cm³
Total porosity: 78.4%
Open or apparent porosity: 38.6%
Saturation coefficient for immersion: 49%

**Dryng shrinkage of AAC:**

It is the dimensional variation (reduction) of AAC test specimens subjected to a drying process starting from a saturated condition until their stabilization in an atmosphere at RH=43%. It was determined on sawed test specimens according to Rilem LC 4-2 test method.

Average drying shrinkage: 0.79 mm/m
Number of determinations: 36
Standard deviation: 0.37 mm/m
Coefficient of variation: 46%
Inferior characteristic value (5% fractil): 0.19 mm/m
Superior characteristic value (95% fractil): 1.39 mm/m

**Compressive strength of AAC:**

It was determined on sawed test specimens, according to Rilem LC 3 test method. The following values were obtained:
Average compressive strength: 2.26 MPa
Number of determinations: 41
Standard deviation: 0.77 MPa
Coefficient of variation: 35.4%
Inferior characteristic value (5% fractil): 0.94 MPa
Superior characteristic value (95% fractil): 3.58 MPa
Average dry density: 519 kg/m³
Average moisture content (dry weight basis): 8.2%

Compressive strength was also determined on complete blocks, according to DIN 4165 test method, previously conditioned in laboratory to reduce their moisture content. The following values were obtained:

Average compressive strength: 2.74 MPa
Average dry density: 424 kg/m³
Average moisture content (dry weight basis): 7.6%

Relationship between compressive strength of complete blocks and sawed test cubes (determined from a same AAC lot) was founded to be 0.81.

**Flexural tensile strength:**

It was determined on test specimens sawed from blocks. Not existing an available test method for this case, the specifications of IRAM 1547:1992 test method were adopted (flexural tensile strength of portland cement concrete). Results were:

Average flexural tensile strength 0.82 MPa
Average dry density: 518 kg/m³
Average moisture content (dry weight basis): 5.6%

On these same blocks test cubes were sawed for determining compressive strength. The relationship between flexural and compressive strength was found to be 0.24 (determined from a same AAC lot).

**Analysis of results**

**Evaluation of physical and mechanical properties of AAC**

Here in advance it is accepted that blocks sampled in the storings and tested in laboratory as it was previously indicated adequately represent that blocks used in housing construction, although differences can exist among different departures of blocks utilized.
Dry density, moisture contents and water absorption.

The apparent density registered for dry condition is relatively low, with an average of 500 kg/m$^3$. It should be taken on account that so smaller density of the hc, so less will be the mechanical resistance of the same one. Nevertheless, a density value is not a parameter that allows to judge itself the quality of material.

On the other hand the dispersion of the obtained results can be positively evaluated. Obviously, a great dispersion of density values is since an index of a great variation on the materials quality, proved that density have an important incidence on the others AAC physical and mechanical properties.

The coefficient of variation of 5.7% corresponding to the 62 tested specimens can be considered as relatively low.

Regarding to the evaluation of such a dispersion, values stated by DIN 4165 may be considered. Table 2 shows values corresponding to AAC blocks of the same type used in this case. Naturally, it is a foreign norm that is not of obligatory application in this case, but it can serve as comparison point.

This table is used to determine if a departure of AAC blocks completes with the requirement of density that should have been established previously using the concept of “density class”. For example, a block specified as 0.5 density class would have a average density between 410 and 500 kg/m$^3$, while no isolated value should be smaller than 360 kg/m$^3$ neither bigger than 550 kg/m$^3$.

For the obtained results the dispersion of results (minimum value: 464 kg/m$^3$, maximum value 585 kg/m$^3$, maximum-minimum differences = 121 kg/m$^3$) is similar to the acceptable one for any density class according to DIN 4165. The average result would correspond to an intermediate value between class 0.5 and class 0.6 according to DIN 4165.

Table 2. Density of AAC blocks according to DIN 4165

<table>
<thead>
<tr>
<th>Strength Class</th>
<th>Density Class</th>
<th>Average density$^1$ (Kg/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.4</td>
<td>310 a 400</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>410 a 500</td>
</tr>
<tr>
<td>4</td>
<td>0.6</td>
<td>610 a 600</td>
</tr>
<tr>
<td></td>
<td>0.7</td>
<td>610 a 700</td>
</tr>
<tr>
<td></td>
<td>0.8</td>
<td>710 a 800</td>
</tr>
<tr>
<td>0.6</td>
<td>0.7</td>
<td>610 a 700</td>
</tr>
<tr>
<td></td>
<td>0.8</td>
<td>710 a 800</td>
</tr>
</tbody>
</table>

$^1$ Individual values must not exceed or be minor of limit values in more than 50 Kg/m$^3$
Regarding to the moisture content of blocks retired from the storings, the obtained value of 34% seems particularly high, since habitually AAC reaches an hygroscopic balance with atmosphere with moisture contents about 5 to 15%. This excessive moisture could be due to:

- absorption of rain water that filtered toward the interior of the storing and -due to the great volume of surrounding material- doesn’t reach to be dissipated later.

- initial presence of an important moisture content in the recently elaborated material, gathered under those conditions that, for the same reasons indicated in the previous case, cannot dry off freely.

Wichever was the case, the setting in place of AAC blocks with such a moisture content presents two important disadvantages:

- the magnitude of total drying shrinkage increases and, consequently, the fissuration risk.

- the mechanical resistance of AAC decreases (a concrete with a moisture content by 30 or 40% may have a compressive strength 20 % smaller than that in dry condition).

Finally, the registered values of absorption (average 78 % in mass, 39% in volume), although normal for this type of AAC, reveal the great capacity of water absorption.

**Drying shrinkage.**

Values obtained are superior to the maxima allowed by DIN 4164 Standard for same type materials. The testing method specified in this standard coincides with that employed in the laboratory determinations (RILEM LC 4-2), and so the obtained results are comparable with the requirements.

Acceptable maximum value according to DIN 4164: 0.5 mm/m
Average value registered: 0.79 mm/m
% of test samples whose results overcome the acceptable maximum: 80%

Thus, an important fraction of tested samples overcame the advisable maximum retraction. It must be said that the same value of 0.5 mm/m as an acceptable maximum is generally accepted by other foreign standards and by specialized bibliography, in which it is suggested to stay considerably below those values. On the other hand, on-site measurements of length variation registered values between 0.10 and 0.20%, corresponding to relatively reduced variations of moisture content in the AAC blocks in the walls.
Compressive strength.

The registered values can be considered as relatively low, considering those obtained on sawed test samples (RILEM LC-3 method, average of 41 test samples: 2.26 MPa) and those obtained on complete blocks (DIN 4165 method, average of 6 blocks: 2.74 MPa).

For evaluation of such results it can be appealed to the requirements of DIN 4165 standard for AAC blocks of the same type that those employed in this case. As it was already indicated in the analysis of the results of density, it is a foreign standard that is not of obligatory application in this case, but it can serve as comparison point. In this standard the resistance requirements are those reproduced in Table 3.

Values on Table 3 are used to decide if an AAC block lot completes the resistance requirement that should have been established previously using the concept of "strength class". For example, a lot of AAC blocks specified as strength class 4 would have an average compressive strength of not less than 5.0 MPa, while each block individually considered would not have a resistance smaller than 4.0 MPa. Blocks of density class 0.4 and 0.5 belong to the strength class 2 while blocks of density class 0.6, 0.7 and 0.8 belong to the strength class 4.

The resistance values to be evaluated according to this approach must be determined from the testing of complete blocks (DIN 4165 method) and not on cubes obtained from the same ones by sawing (RILEM LC-3 method). Results obtained by the second method (employed in most of tests that integrate this study) are habitually bigger than those obtained using the first one (whole blocks). It was verified determining a relationship of 0.8 for one lot of blocks.

In this case there is not a previous resistance specification that allows to carry out an evaluation of acceptance or rejection. From the limited point of view of strength, blocks could be classified as class 2, as long as its average strength would overcome the demanded value of 2.5 MPa. Nevertheless, the inclusion in this strength class (the minimum category settled down by DIN 4165) would not

**Table 3. Strength requirements for AAC blocks according to DIN 4165**

<table>
<thead>
<tr>
<th>Strength Class</th>
<th>Compressive strength (MPa)</th>
<th>Density Class</th>
<th>Average density(^1) (Kg/m(^3))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min average</td>
<td>Min individual value</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>2,5</td>
<td>2,0</td>
<td>0,4</td>
</tr>
<tr>
<td></td>
<td>0,5</td>
<td>410 a 500</td>
<td>0,6</td>
</tr>
<tr>
<td></td>
<td>0,7</td>
<td>610 a 700</td>
<td>0,8</td>
</tr>
<tr>
<td>4</td>
<td>5,0</td>
<td>4,0</td>
<td>0,7</td>
</tr>
<tr>
<td></td>
<td>0,8</td>
<td>710 a 800</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>7,5</td>
<td>6,0</td>
<td>0,7</td>
</tr>
<tr>
<td></td>
<td>0,8</td>
<td>710 a 800</td>
<td></td>
</tr>
</tbody>
</table>

\(^1\) Individual values must not exceed or be minor of limit values in more than 50 Kg/m\(^3\)
be valid since numerous individual test results would not reach the demanded value of 2.0 MPa and, on the other hand, density values exceed the limits allowed for this strength class.

Another point of reference is that established by RILEM Recommendation LC 2 in its functional classification of lightweight concretes. For AAC intended not only for insulating functions but also for support (class II) it demands a compressive strength of not less than 2.5 MPa, although it clarifies that in some countries this requirement can be smaller. Thus, also in this case the obtained results would be below the inferior limit of the requirements. In this regard, it must be indicated the scarce regulation in our region, compared to European standardization (Bright, 1992).

In the previous considerations the standards requirements are compared with the average results, but an aspect of not little importance that should be considered is the considerable dispersion registered. The 41 tested samples group presented an extremely high dispersion coefficient: 35%. To illustrate the situation it can be said that for statistically establishing an interval of values comprising the 90% of results, margins so wide as 0.94 MPa (inferior limit) and 3.58 MPa (superior limit) should be taken. This inferior limit of 0.94 MPa corresponds to that habitually defined as “characteristic strength” of concrete.

From the point of view of structural calculation of housing subjected to habitual loads (weigh of walls and roof, wind effect, etc.), it could be said that these values are acceptable since actual loads transmitted to walls are very low (for example compressive strengths by 0.1 to 0.5 MPa). This would give sufficiently high margins of security. Nevertheless, these mechanical resistances could be insufficient taking on account the great dispersion of values and other factors like efforts concentration in critical points, volumetric variations, foundations movements, etc.

On the other hand, the demand of a certain value for compressive strength exceeds the simple verification of a relationship between calculation strengths and admissible strengths. Indeed, since practically all AAC mechanical properties relate to compressive strength, the imposition of a resistance requirement implies, indirectly, the imposition of a certain quality level. In fact, if a AAC has a bigger compressive strength it will have a better mechanical performance, including more rigidity and better resistance to another type of solicitations, such as tensile strength due to blocks drying shrinkage in masonry.

Evaluation of the cracking risk due to drying shrinkage

As it was mentioned in the previous section, the shrinkage values registered in test samples were relatively high. The natural consequence of an excessive contraction is the formation of fissures or cracks that appear when shortening of material (caused by its moisture loss) cannot be carried out freely due to the presence
of restrictions to movement (for example: presence of openings, structural reinforcements, constructive elements of different rigidity, etc.). In this situation tensile stresses are generated into the AAC. If it overcome the materials resistance to such efforts, it cause the break of the same one with the subsequent formation of flaws.

Starting from the analysis of tensile strength it can be considered which it is the acceptable maximum shrinkage so that fissures don't take place, assuming the material is able to move freely:

\[ e_{\text{max}} = \frac{S_t}{E_b} \]

Where:

- \( e_{\text{max}} = \) acceptable maximum specific deformation (in this case due to shrinkage) to avoid formation of cracks
- \( S_t = \) materials tensile strength (in MPa)
- \( E_b = \) materials longitudinal module of elasticity (in MPa)

According to different sources, the value of tensile strength for this case can be considered grossly between 0.3 and 0.8 MPa, (like a certain fraction of the compressive strength, nearer to lower value than to upper). Results of flexural tensile strength confirm this estimate, since resistance to direct traction is habitually smaller than flexural tensile strength. From the relationship flexural strength / compressive strength = 0.24 obtained on samples, it can be considered an average flexural strength (for the group of samples) of 0.24 x 2.26 MPa = 0.54 MPa, with a direct tensile strength below this last value. A punctual experience on a single sample of AAC brings a result of 0.25 MPa.

On the other hand, module of elasticity may be considered between 1.000 and 1.300 MPa depending on density and compressive strength.

With these values an acceptable maximum shrinkage ranging from 0.2 to 0.8 mm/m is calculated, probably more near the lower limit than the upper. This “admissible” value would be overcome by the great majority of tested samples. The situation becomes worse for the critical limits of moisture in AAC blocks if they are placed with a high initial moisture content or if AAC is subjected to an intense drying due either to aeration or sun exposure.

Another way to focus the same situation is to calculate which are the tensile stresses that are generated as a consequence of a certain shrinkage:

\[ S_t = e_{\text{max}} \times E_b \]

Using in this equation the average shrinkage values obtained in tests and the same estimate of module of elasticity, variable tensile stresses between 0.8 and 1.0 MPa are obtained, that surely overcome the materials tensile strength.
In conclusion, it is very probable that if free movement of AAC is limited (as in fact it happens in different points of the walls) the shrinkage, accentuated by important changes in moisture content of the material, cause the fissure formation. As it is pointed out in other antecedents (Nielsen, 1983) this conclusion may be attenuated keeping in mind that in many cases the movement restriction is not absolute and the effective tensile stresses may be diminished by the effect of creep, taking on account the low speed of the drying and shrinkage process.

Another necessary observation is that, as recent studies have demonstrated (Gottfredsen et al., 1997), the magnitude of drying shrinkage from saturation state is not the same one in the original process from the material production that in any other later similar process.

The effect of the shrinkage would explain an important part of fissures detected in both housing groups. In one of the groups, the use of an hydraulic protection of less effectiveness that in the other one, would justify a worsening of symptoms (bigger variations on moisture content, bigger shrinkage and bigger formation of fissures). The delayed or faulty repair of these fissures would leave an open access to moisture and subsequent damages.

Finally it can be pointed out that many important vertical fissures were detected, whose superior and inferior ends close inside the same wall. Therefore, this cracks cannot be due to global movements of the construction (since in such a case it would have some of its ends opened) but only to dimensional variations of material, like in the case of shrinkage. Thermal expansions and contractions are discarded as cause of cracks taking on account their scarce relative value, estimated from the coefficient of thermal expansion of AAC (similar to that of normal concrete) and the habitual temperature variations in the area.

It is important to highlight that a very frequent type of crack consist in fissures bowed at the ends of the walls, with such characteristics that can be awarded without any doubt to differential movements in the construction, due to soil expansibility. In order to quantify the deformations and the efforts that soil movements can cause in the walls, it was carried out a mathematical analysis by means of computer program using the finite elements theory (Lenz et al., 1996) wich presentation exceeds the limits of this work.

CONCLUSIONS

In final synthesis, and as it has already been indicated, the detected pathologies have taken place due to two causes that have completely different origins but are concomitant, that is:

- movements of the expansive foundation soils, causing deformations in foundation slabs that cannot be appropriately absorbed by the AAC blocks walls,
since it not present values of mechanical resistance compatible with the induced solicitations.

• shrinkage of AAC, caused by the initial drying of the blocks placed with an important moisture content or by later variations of this content, generating tensile stresses that overcome the materials tensile strength, with subsequent formation of fissures.

Looking at the objective of the present work, the second cause of detected pathologies is highlighted. Thus, the housings durability was affected by inadequate values of a parameter like AAC shrinkage, which importance is habitually undervaluated.

REFERENCES


