Autoclaved aerated concrete for masonry constructions of residential buildings

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Since the invention of Autoclaved Aerated Concrete (AAC) in the early 20th century this building material has been continuously developed in order to improve its technical and physical properties. Today's production technologies are able to control the amount and size of pores precisely so that AAC-blocks with a density from ρ = 350 kg/m³ to ρ = 650 kg/m³ and a compressive strength from 2 MPa to 6 MPa are available for the construction of residential buildings. For single family houses AAC-masonry with a density of 250 kg/m³ is available. Special AAC insulation products for enhancement of existing buildings with density of ρ = 50 - 90 kg/m³ and thermal conductivity λ = 0,042 W/(mK) entered the market recently. Due to its structure – basically a mineral foam with approx. 20 % solid material and approx. 80 % pores – AAC shows in comparison to other building materials a different behavior with respect to thermal and acoustic properties.

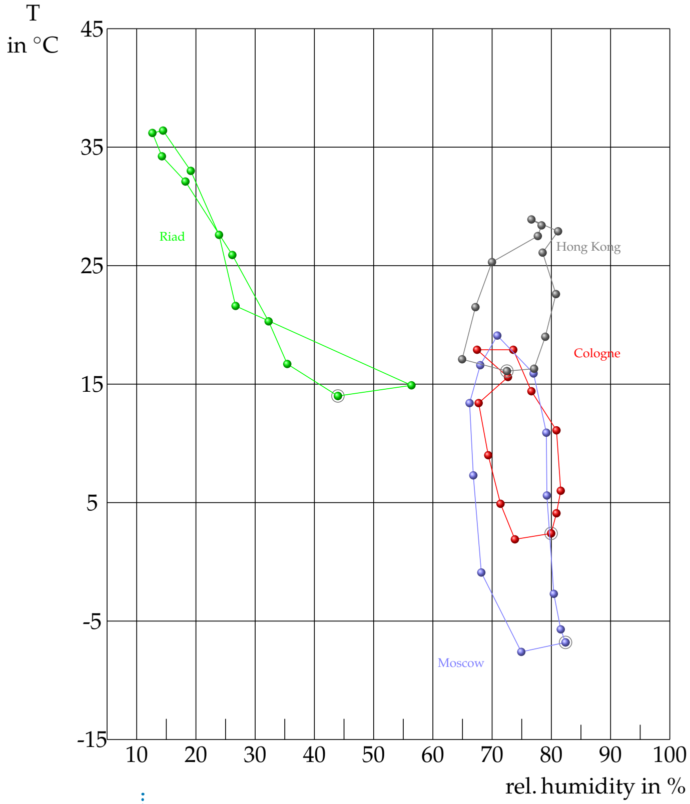

Fig. 1: Outdoor air temperature (dry bulb) and relative humidity daily mean values, calculated from hourly mean values Data taken from EnergyPlusWeather Data.

Energy efficiency and thermal comfort

According to the European Commission [1] approximately 40 % of energy consumption and 36 % of CO_2 emissions are due to the operation of buildings and its HVAC (Heating, Ventilation and Air Conditioning) systems, making the occupation and use of buildings the largest single source of EU greenhouse gas emissions, mainly in the form of carbon dioxide. The matter by itself is not surprising as the inherent purpose of buildings is to maintain a constant indoor climate under changing outdoor conditions. However, the necessary amount of energy is highly dependent on the energy performance of the building shell which is described by the heat transfer coefficient (U-value) [2]. In order to significantly reduce energy consumption and CO_2 emissions, the European Commission has updated the Energy Performance of Buildings directive recently [3,4,5]. The requirements have to be implemented into national legislation until March 2020 and will most likely put emphasis on refurbishment or renewal of existing buildings and HVAC systems. The calculation scheme to assess energy efficiency of buildings is not limited to heat losses by transmission but also takes into account ventilation losses, energy consumption for hot water supply, solar and internal gains and the type and efficiency of the heating / cooling system. Hence, it is possible to compensate poor insulation by a state-of-the-art boiler and vice versa or to improve roof insulation and reduce the thickness of insulation layers in exterior walls. Especially in the case of single-family houses architects often choose a brick outer leaf for reasons of architectural design, durability and resistance against wind driven rain penetration. Depending on the choice of materials for the load bearing structure and the insulation layer, wall thickness increases and may reach values of more than 45 cm. However, AAC-masonry with low thermal conductivity [6], i.e. $\lambda \leq 0{,}120$ W/(mK), makes it possible to meet ambitious energetic requirements with a total wall thickness $d \approx 40$ cm. Typical cross sections consist of an inner leaf made with AAC blocks ($d = 17{,}5$ cm, $\rho = 500$ kg/m³, $\lambda \leq 0{,}120$ W/(mK)) a core-insulation ($d = 10$ cm, $\lambda \leq 0{,}035$ W/(mK)) and the brick outer leaf ($d = 11{,}5$ cm, $\rho = 1800$ kg/m³, $\lambda \approx 0{,}81$ W/(mK)). Together with the inner plaster layer such walls have a heat transfer coefficient $U = 0{,}20$ W/(m²K).

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HVAC systems can usually be regarded as independent from the building shell and structure. However, well insulated buildings offer many more options concerning size, type and supply temperature of the heat exchangers, e. g. floor heating. In most European regions the energy consumption is mainly determined by heating (cf. Fig. 1, Tab. 1). The heating period usually lasts from September to April. Especially in fall and spring, the ability of buildings to buffer solar gains during sunny days may significantly reduce their energy consumption because the heating system can be switched off. By use of solar collectors even the hot water tank is supplied independently. Sample calculations [7] have shown that depending on the building type (residential or office), the calculation method (quasi steady state method or dynamic calculation), the number and the orientation of windows a heavyweight building structure with good thermal insulation of the shell requires 2 – 9 % less primary or bought energy (1.5 to 6 kWh/(m²a)) in comparison to an equivalent lightweight construction. This is explained by the ability of heavyweight buildings to buffer almost 100 % of the available solar energy at moderately increased levels of indoor temperature because $\Delta T = Q/(c \cdot m)$. In the same manner increased ventilation during night hours can

Tab. 1: Collected data acc. to figure 1

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Cologne	T [°C]	2,4	1,9	4,9	9,0	13,4	15,6	17,9	17,9	14,4	11,1	6,0	4,1
	r.F. [%]	83,3	76,5	73,8	71,5	69,7	75,2	69,4	76,2	79,6	84,3	85,1	84,3
Berlin	T [°C]	1,9	0,3	5,4	8,3	14,0	17,6	19,1	18,5	15,0	10,2	4,4	2,4
	r.F. [%]	80,4	80,5	77,8	69,8	63,8	64,5	63,1	65,5	70,6	76,8	83,0	86,6
Sydney	T [°C]	24,3	24,0	21,6	18,7	16,2	15,6	12,5	13,7	15,9	18,8	19,1	20,5
	r.F. [%]	68,9	69,1	66,2	64,6	76,0	67,3	63,6	49,4	53,1	62,1	61,2	68,7
Hong Kong	T [°C]	16,1	16,3	19,0	22,6	26,1	27,9	28,9	28,4	27,5	25,3	21,5	17,1
	r.F. [%]	75,0	80,1	82,2	84,2	81,7	84,6	79,6	81,5	80,8	72,2	69,1	66,6
Stockholm	T [°C]	-3,5	-0,8	0,3	4,5	11,7	14,5	17,0	16,0	11,3	6,7	1,6	-1,9
	r.F. [%]	90,7	78,6	84,3	65,4	63,5	68,0	73,0	72,3	81,8	85,8	88,2	88,5
Washington	T [°C]	-0,6	1,5	5,8	10,9	16,4	22,6	24,5	23,7	20,4	13,9	7,9	1,7
	r.F. [%]	66,0	71,0	56,6	60,3	60,4	66,4	71,3	72,9	66,9	70,9	66,4	67,2
Riad	T [°C]	14,0	16,7	20,3	25,9	32,1	35,2	36,2	36,4	33,0	27,6	21,6	14,9
	r.F. [%]	43,3	33,8	30,3	23,5	14,7	12,0	8,5	10,5	15,7	21,0	24,1	57,1
Moscow	T [°C]	-6,8	-7,6	-0,9	7,3	13,4	16,6	19,1	15,9	10,9	5,7	-2,7	-5,7
	r.F. [%]	86,0	77,7	70,2	68,7	68,0	70,0	73,2	80,0	82,4	82,5	83,8	85,1
Dakar	T [°C]	20,2	20,3	20,9	21,3	23,0	25,1	27,0	27,3	27,7	27,5	25,9	23,1
	r.F. [%]	64,9	72,7	79,1	83,6	85,0	83,3	78,8	84,8	81,6	79,7	76,3	70,6
Lima	T [°C]	22,5	23,2	23,1	20,9	19,2	18,5	17,0	16,6	17,1	17,8	19,3	21,4
	r.F. [%]	76,8	80,1	79,2	81,1	81,1	81,3	80,1	84,8	83,3	83,5	80,2	76,5

Source: EnergyPlus Weather Data (https://energyplus.net/weather)
Calculated from hourly mean values Data taken from EnergyPlusWeather Data.

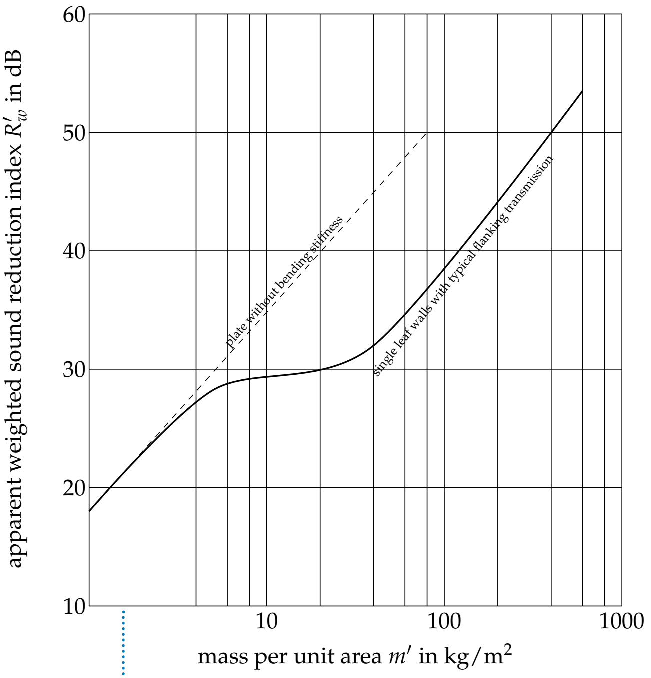


Fig. 2: Apparent weighted sound reduction index in relation to mass per unit area

cool down internal buildings structures and create a phase shift of peak temperatures so that cooling devices may become redundant.

In addition to energy efficiency these constructions are very advantageous with regard to thermal comfort. According to ISO 7730 [8] thermal comfort is defined as “the condition of mind which expresses satisfaction with the thermal environment”. Thermal comfort can be quantified by the comfort equation stating that heat production by the human body and heat losses – by evaporation, respiration, heat conduction through clothing, radiation and convection – have to be in equilibrium [9]. From the comfort equation it is obvious that thermal comfort of a person is mainly influenced by the metabolic rate, i.e. the heating system of a human body, and clothing, i.e. the insulation layer of a human body. In addition, the properties of the indoor air (temperature, rel. humidity, velocity) and the inner surfaces of an enclosure *(surface temperature and emission factor of walls, floor and ceiling)* play an important role either. Considerable differences between surface temperatures of walls, floor and ceiling are perceived as uncomfortable and – if the differences exceed a certain limit – may even lead to misperception i.e. draught. As a consequence, thermal comfort can only be achieved if the heat transfer coefficient (U-value) of every boundary surface – and not only the mean U-value – meets the requirements for sufficiently high surface temperatures. Besides thermal properties of opaque partitions of exterior walls, glazing and heaters have to be considered during the planning process. It is obvious that triple glazing and floor heating systems reduce radiation asymmetry and improve thermal comfort (cf. Tab. 2). Given the fact that people spend most of their lifetime inside buildings it is obvious that thermal comfort and energy efficiency of buildings must be regarded as equally important issues in the design process.

Acoustic properties

The most important acoustic property of masonry walls is the sound reduction index which may be determined in frequency bands (1/3 octave, full octave) or as a single value obtained from a weighting procedure. Theoretically the weighted sound reduction index of solid masonry walls increases according to Berger’s law by 6 dB when doubling the mass per units area (cf. Fig. 2). Due to inevitable resonance effects (coincident waves, cf. Fig. 3) the actual increase varies depending on mechanical and geometrical properties of the wall. In addition, porous materials show some peculiarities resulting from the discontinuities between air filled pores and solid state cell walls. The acoustic behavior of solid AAC masonry walls has been investigated in a series of laboratory tests [11]. As a result, the weighted sound reduction index can be determined by a material specific equation (mass law for AAC masonry), taking into account the mass per unit area (m’) of the wall. For walls with 50 kg/m² ≤m’ ≤ 300 kg/m² the weighted sound reduction index can be calculated by the following formulas [10]
The evaluation of these formulas is shown in Fig. 4. As a reference the mass law for walls of non-porous

Tab. 2: Temperatures of inner surface for AAC masonry and glazing

				36,5 cm AAC plaster on both surfaces	**17,5 cm AAC, 10 cm mineral wool, plaster on both surfaces**	**triple glazing sealed units**	**double glazing sealed units**	**single glazing**
			u-value	0,209 [W/(m²K)]	0,202 [W/(m²K)]	0,800 [W/(m²K)]	1,200 [W/(m²K)]	6,000 [W/(m²K)]
		$T_{air,i}$	$T_{air,e}$	$T_{s,i}$	$T_{s,i}$	$T_{s,i}$	$T_{s,i}$	$T_{s,i}$
Climate and air temperature inside/outside	Europe winter	20 °C	-10 °C	19,2 °C	19,2 °C	16,9 °C	15,3 °C	-3,4 °C
	northern hemisphere winter	20 °C	-15 °C	19,0 °C	19,1 °C	16,4 °C	14,5 °C	-7,3 °C
	tropical summer	20 °C	30 °C	20,3 °C	20,3 °C	21,0 °C	21,6 °C	27,8 °C
	desert summer	20 °C	40 °C	20,5 °C	20,5 °C	22,1 °C	23,1 °C	35,6 °C

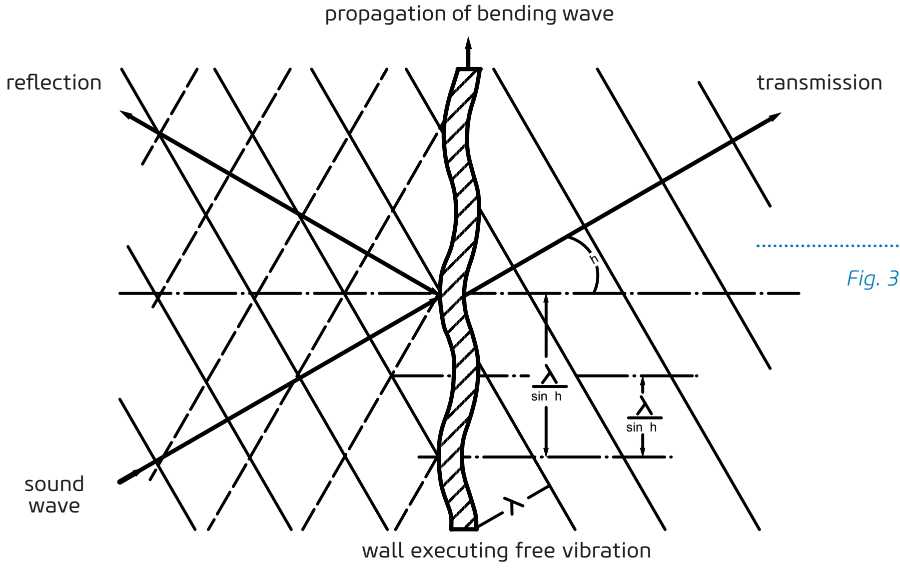


Fig. 3: Coincident waves

$$R_w = 32{,}6 \cdot \lg \frac{m'}{1\ \mathrm{kg/m^2}} - 22{,}5\ \mathrm{dB}$$

$$\text{if} \quad 50\ \mathrm{kg/m^2} \leq \mathrm{m'} \leq 150\ \mathrm{kg/m^2} \qquad (1)$$

$$R_w = 26{,}1 \cdot \lg \frac{m'}{1\ \mathrm{kg/m^2}} - 8{,}4\ \mathrm{dB}$$

$$\text{if} \quad 150\ \mathrm{kg/m^2} < \mathrm{m'} \leq 300\ \mathrm{kg/m^2} \qquad (2)$$

masonry and concrete walls is included in the diagram.

For further improvement of the sound reduction index double-leaf constructions are mandatory. This wall type is mainly used for facades exposed to traffic noise and separating party walls between attached houses. Unlike single leaf walls with coincidence effect these constructions can be tuned to a specified resonance frequency by adjusting the mass per unit area m' of the leaves and the dynamic stiffness s' of the cavity in between to the desired values. As an estimate for the resonance frequency

$$f_0 = 160 \sqrt{\frac{0{,}08}{d}\left(\frac{1}{m'_1} + \frac{1}{m'_2}\right)}\ \mathrm{Hz} \qquad (3)$$

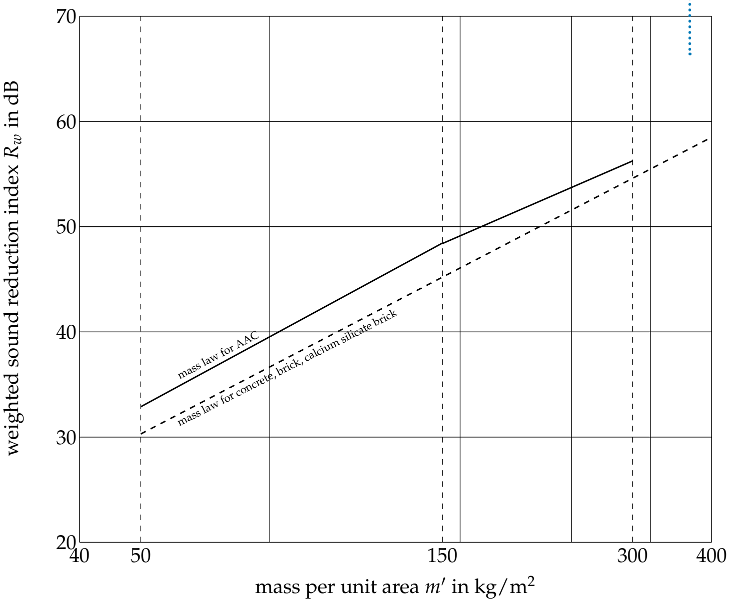
is given in [12] where d is the depth of the cavity in [m], m'_1 and m'_2 are the specific masses of the leaves in [kg/m²]. This leads to an improvement of the sound reduction index [11]

$$R_w = 74{,}4 - 20 \cdot \lg f_0 - 0{,}5 \cdot R_w \geq 0\ \mathrm{dB}$$

with f_0: resonance frequency

R_w: sound reduction index of basic leaf (4)

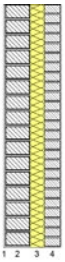
Fig. 4: Weighted sound reduction index in relation to mass per unit area

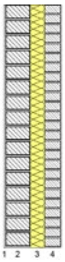


It can easily be seen that typical exterior walls as already described in the previous section have a weighted sound reduction index R_w ≈ 57 dB. This value may vary depending on the wall ties, e.g. steel needles, between the two leaves and the stiffness of the insulation layer. Windows and other openings in exterior walls reduce the sound reduction index significantly.

Separating party walls between attached houses are mostly built as cavity walls. Further improvement of the sound reduction index is achieved if the cavity is filled with mineral wool. In any case sound bridges by accidentally left mortar pieces have to be avoided, because otherwise the cavity wall changes its acoustic behavior to that one of a single leaf wall. The disadvantageous but inherent property of AAC-masonry walls – a low specific mass – is partly compensated by two special effects. First the particular mass law for AAC yields – in comparison to non-porous materials – slightly higher values for the sound reduction index (cf. Fig. 4). Second the discontinuity in impedance at connections to concrete

Tab. 3: Specific values of the exterior walls

Building component:		North Wall; Middle		area/direction:		**7,16 m²** **N**
	Nr.	Building material	Thickness	Lambda	Density	Thermal resistance
	1	plaster mortar from lime, lime cement and hydraulic lime	1,50	1,000	1800,0	0,02
	2	AAC-blocks (PP, DM…) (400 kg/m³)	17,50	0,100	400,0	1,75
	3	Miner. and vegetable fibre insulating materials (DIN 18165-1 - WLG 035)	10,00	0,035	260,0	2,86
	4	Solid brick, vertically perforated brick, filler brick (1400 kg/m³)	11,50	0,580	1400,0	0,20
		Requirement acc. to DIN 4108 Part 2 is fulfilled		**$R_{\lambda,zul.}$ = 1,20**		**R_{λ} = 4,82**
		Building component area	mass per unit area	specific transmission heat loss	Effective heat storage capacity	R_{si} = 0,13 R_{se} = 0,04
		7,16 m² 1,2 %	284,0 kg/m²	1,43 W/K 0,9 %	10cm-rule : 121 Wh/K 3cm-rule : 66 Wh/K	U-value = **0,20 W/(m²K)**

Building component:		South Wall; Middle East Wall West Wall		area/direction:		**4,51 m²** **S** **37,27 m²** **E** **30,74 m²** **W**
	Nr.	Building material	Thickness	Lambda	Density	Thermal resistance
	1	Gypsum plaster without additions	1,50	0,510	1200,0	0,03
	2	AAC-blocks (PP, DM…) (400 kg/m³)	17,50	0,130	400,0	1,35
	3	Miner. and vegetable fibre insulating materials (DIN 18165-1 - WLG 035)	10,00	0,035	260,0	2,86
	4	Solid brick, vertically perforated brick, filler brick (1400 kg/m³)	11,50	0,580	1400,0	0,20
		Requirement acc. to DIN 4108 Part 2 is fulfilled		**$R_{\lambda,zul.}$ = 1,20**		**R_{λ} = 4,43**
		Building component area	mass per unit area	specific transmission heat loss	Effective heat storage capacity	R_{si} = 0,13 R_{se} = 0,04
		72,53 m² 12,0 %	275,0 kg/m²	15,76 W/K 9,8 %	10cm-rule : 1048 Wh/K 3cm-rule : 484 Wh/K	U-value = **0,22 W/(m²K)**

slabs reduces the sound transmission via joints in comparison to homogeneous constructions using materials of identical impedance. This fact is especially important for single family houses without basement because they are lacking a complete separation of the base slab and/or the foundation. Even with this kind of unavoidable sound bridge a sound reduction index R_w ≈ 62 dB can be achieved by two leaves of AAC-masonry with 24 cm thickness [13]. It is further advisable to detune separating party walls between attached houses by assigning different thickness to the leaves, e.g. 17,5 cm and 24 cm.

For any kind of sound transmission in buildings the contribution of flanking walls and slabs must not be neglected. This additional sound transmission may reduce the sound reduction index by several dB, depending on the coupling between separating wall and flanking parts.

Single-family house in Cologne, Germany, an example for good practice

In the neighbourhood of St. Heribert, a neoromanic church in Cologne, a modern single-family house has been built by Architect Martin Wendling in the years 2015/2016. On the building plot, located inside a patio, was an accommodation for workers since the 1960s which had reached its end of life. Instead of demolishing the existing buildings their structural work was integrated into the ensemble of the new building, the brick wall separating the churchyard of St. Heribert and the single storey annex buildings of the neighborhood. For this purpose, a new saddle roofed building was added to existing flat-roof building. The main building is slightly higher and emphasizes the T-shaped floor plan. The exterior walls consist of a 17,5 cm thick AAC-masonry inner leaf,

Construction site of the single-family house

Exterior view of the finished building

Interior view

10 cm core insulation (mineral wool) and a 11,5 cm thick clinker façade (see Tab. 3). The roof with minimalistic overhang is covered with zinc metal sheets. In combination with the grey colored window sills in basaltic lava from the Eifel region and the window frames made of bright larch wood a pleasant scene is presented to visitors. The inner surfaces of the AAC-walls are covered with natural lime plaster providing a bright white, even and comfortable interior. An entrance hall with staircase separates the open plan living room with kitchen from a private section with bath and bedrooms.

The estimated annual amount of bought energy for the building is Q_E = 17.333 kWh/a including 601 kWh for hot water supply. Because the building is connected to a district heating that uses mainly renewable energy sources the estimated annual amount of primary energy is only Q_P = 1450 kWh/a. With reference to the usable floor space (A_N = 200,7 m²) the estimated annual amount of primary energy Q''_P = 7,2 kWh/(m²a) and the specific heat transmission loss coefficient H'_T = 0,316 W/(m²K) are 30 % lower than the allowable limit values according to the national energy efficiency regulations.

Conclusion

Autoclaved aerated concrete as a building material for masonry constructions of residential buildings offers robust technical solutions for exterior walls with high energy efficiency and a high level of noise protection. These properties are not only favorable for the construction of new buildings but also in the case of refurbishment and renewal of buildings, a growing market driven by Energy Efficiency regulations. The single family house in Cologne with its extraordinary architectural impression is a good example for the versatility that can be obtained by a combination of AAC masonry with additional facade materials.

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Interior view