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# SALT IN BUILDING CONSTRUCTION:
# Literature review, hygrothermal performance and application in 3D printing

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# Abstract

The shortage of building materials is a challenge that has already been addressed in many countries in recent decades. Population growth, climate changes, and unexpected situations such as COVID-19 and the war in Ukraine have accelerated this phenomenon. The world population is expected to reach 8.5 billion in 2030 [1], and the difference between human demand and nature's capacity is large. People use natural resources as if they have more than one earth at their disposal [2]. However, the negative effects of population growth and resource scarcity can also be turned into positive ones by identifying materials that are generated as by-products in industry and can replace the rare materials.

One of these promising new materials is sodium chloride (salt), which is produced in large quantities as a waste product from potash mining and seawater desalination. The salt from these two processes is now being disposed of into the natural environment with negative impacts on the environment (increase in salinity and temperature of water, reduction in biodiversity, and even destruction of plants and aquatic life at high concentrations [13–15]).

The use of salt is common, especially in the food and chemical industries. Many associate salt in the thermal envelope with material damage due to salt crystallization, solubility risks, and corrosion. This cumulative dissertation is therefore dedicated to finding answers to these challenges. In the first step of the thesis, relevant examples of salt materials and their applications in building history are identified from the literature review. The 2,000-year-old salt-clay walls from Egypt, Roman maritime concrete in the Mediterranean area and salt concrete from Germany are just some of many examples that are discovered. One of the most suitable salt materials that has already been used in interior applications is available on the market and has a high salt content is Himalayan salt. Its material properties are analyzed at the Fraunhofer Institute IBS and used for the study of hygrothermal analysis of salt. In a second step, the solubility risk was investigated by studying which climatic conditions are suitable for indoor salt application and what effects this has on moisture and heat transport in the thermal envelope, indoor air quality and energy consumption. After finding that salt application is advisable in very hot and dry climates, a case study on the use of salt materials with 3D printing is explored, where including building with highly porous materials and innovative reinforcements is possible.

The results show that salt has potential for use in building construction, and achieving a better understanding of its historical examples, hygrothermal properties, and use in 3D printing could increase its acceptance.

# Zusammenfassung

Mangel an Baumaterialien ist eine Herausforderung, die in vielen Ländern bereits in den letzten Jahrzehnten angegangen wurde. Bevölkerungswachstum, Klimawandel und unerwartete Situationen wie COVID-19 und der Krieg in der Ukraine haben dieses Phänomen beschleunigt. Die Weltbevölkerung wird im Jahr 2030 voraussichtlich 8,5 Milliarden betragen. Die Differenz zwischen menschlichem Bedarf und der Kapazität der Natur ist groß. Die Menschen nutzen die natürlichen Ressourcen so, als hätten sie mehr als eine Erde zur Verfügung. Die negativen Auswirkungen des Bevölkerungswachstums und der Ressourcenknappheit können jedoch auch ins Positive umgewandelt werden, indem Materialien identifiziert werden, die als Nebenprodukte in der Industrie entstehen und die seltenen Materialien ersetzen können.

Eines dieser neuen vielversprechenden Materialien ist Natriumchlorid, das in großen Mengen als Abfall beim Kalibergbau und bei der Meerwasserentsalzung anfällt. Nun wird Salz aus diesen beiden Prozessen in die Natur entsorgt und hat negative Auswirkungen auf die Umwelt (eine Erhöhung des Salzgehalts und der Wassertemperatur, eine Verringerung der Veränderung der Biodiversität und bei einer hohen Konzentration sogar eine Zerstörung von Pflanzen und Wasserlebewesen).

Die Verwendung von Salz ist vor allem in der Lebensmittel- und chemischen Industrie üblich. Der Einsatz im Bau ist nach wie vor mit Mauerwerksschäden, Löslichkeits- und Korrosionsrisiken verbunden. Diese kumulative Dissertation widmet sich daher der Suche nach Antworten auf diese Herausforderungen. Im ersten Schritt der Arbeit werden aus der Literaturrecherche die guten Beispiele für Salzmaterialien und deren Anwendungen in der Baugeschichte identifiziert. Die 2000 alten Salzlehmwände aus Ägypten, römischer Meerbeton im Mittelmeerraum und Salzbeton aus Deutschland sind nur einige von vielen, die entdeckt werden. Eines der am besten geeigneten Salzmaterialien ist Himalaya Salzstein, das bereits im Innenbereich angewendet wurde und auf dem Markt erhältlich ist und einen hohen Salzgehalt hat. Seine Materialeigenschaften werden am Fraunhofer Institut IBS analysiert und für die Untersuchung der hygrothermischen Analyse von Salz verwendet. Im zweiten Schritt wurde das Löslichkeitsrisiko angegangen, indem untersucht wurde, welche Klimabedingungen für die Anwendung von Salz in Innenräumen geeignet sein könnten und welche Auswirkungen dies auf den Feuchtigkeits- und Wärmetransport in der thermischen Hülle, die Raumluftqualität und den Energieverbrauch hat. Nachdem festgestellt wurde, dass

die Anwendung von Salz bei sehr heißen und trockenen Klimabedingungen ratsam ist, wird eine Fallstudie zur Verwendung von Salzmaterialien mit 3D-Druck untersucht, bei der auch das Bauen mit hochporösen Materialien und innovativer Verstärkung möglich ist.

Die Ergebnisse zeigen, dass Salz ein Potenzial für den Einsatz in der Baubranche aufweist. Ein besseres Verständnis seiner historischen Beispiele, hygrothermischen Leistungen und Verwendung im 3D-Druck verbessert seine Akzeptanz.

# Contents

# Abbreviations

| | |
|---|---|
| A | Area (m2) |
| $c_p$ | Specific heat capacity (kJ/(kg K)) |
| d | Thickness (m) |
| H | Total enthalpy (J/m3) |
| $h_v$ | Evaporation heat of water (J/kg) |
| p | Partial pressure of water vapor (Pa) |
| T | Temperature (°C) |
| t | Time (s) |
| $\vartheta$ | Surface temperature |
| $\delta$ | Water vapor transfer coefficient (kg/(m s Pa)) |
| $\lambda$ | Thermal conductivity (W/(m K)) |
| $\mu$ | Water vapor diffusion resistance factor of a building material |
| $\rho_l$ | Density of water in liquid form (kg/m3) |
| RH | Relative humidity (%) |
| $\partial$ | Operator for partial differential |
| | |
| HVAC | Heating, Ventilation and Conditioning |
| HAM | Heat, Air and Moisture |

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# 1 Introduction

In this section, the most important reasons for the study of salt are highlighted. The world's population is growing and there is a shortage of natural resources, while salt waste is increasing and causing environmental pollution. These two challenges offer the potential for the use of salt waste as a new resource.

This work deals with a consideration to apply salt in construction. The main focus is to identify the most suitable salt material from the literature, analyse its hygrothermal behavior and highlight its potential with new construction technologies.

Thesis outline:

**Chapter 1:** Introduction. This chapter provides an overview of the research problem, the research objective, and the outline of the thesis. It shows that there is sufficient salt waste that can be used as a new building material and explains the importance of hygrothermal studies of the material.

**Chapter 2**: Research methodology. This chapter presents an overview of the research methodology, organized in a step-by step approach. In the first step, a systematic literature review of salt materials used in construction is provided, the advantages and disadvantages of the materials are discussed, and the most promising salt materials for interior applications are highlighted. Regarding hygrothermal performance and its influence on indoor air quality and energy demand, in the second step experimental studies and simulation studies are conducted to illustrate the hygrothermal performance of salt in the thermal envelope. Experimental studies help to understand the material behavior of salt and allow a comparison between simulation and measured results. The overall goal of the simulation is to provide information on how salt affects building design, indoor living conditions, and energy demand. Heat and moisture transport in the thermal envelope during natural weathering is simulated with WUFI®Pro, and influences on indoor air temperature and relative humidity with WUFI® Plus. In the third step, the scope, methods and results concerning the application of salt in 3D printing are illustrated. The main motivation for this chapter is to use salt as an alternative material in additive manufacturing to improve the resource efficiency of the building materials. To achieve this aim, the first case study of a small-scale 3D printing with paste extrusion is conducted. Summaries of four publications are presented in each step. First, *Salt* *as a Building Material: Current Status and Future Opportunities* illustrates the data for the first step, before *Hygrothermal Performance of Salt (NaCl) for Internal Surface Applications in the Building Envelope* presents the methods, results, and discussion of experimental and simulation results for the second step. Two papers – *Reuse of salt waste in 3D printing: Case study* and *3D print with salt* discuss and show information for the third step. Two papers are presented because the latter paper is still in the publishing process and is to be finalised in September 2022.

**Chapter 3:** Discussion, Conclusion and Future work. This chapter discusses the results of the thesis, and outlines the limitations and potentials of this work, including recommendations for further study and implications for research.

**Chapter 4:** Bibliography

**Chapter 5:** Appendix A. Full texts of the publications are presented.

**Chapter 6:** Appendix B. The signed declaration of contribution for the four papers is presented.

**Chapter 7:** Appendix C. Supplementary studies on the salt material mixtures are presented. The goal of this study was to evaluate how salt influence the quality of salt-gypsum mixtures. The experimental study deals with defining the mixing ratio of salt and binders and testing its compressive strength, helping to understand salt materials.

**Chapter 8:** Appendix D. Study of the influence of salt on performance during climate fluctuations. In this study, the variations in weight of three materials (salt, gypsum, salt-gypsum) during the humidity fluctuation at two different temperatures were investigated to analyze the durability of materials for indoor application and collect the hygrothermal information for comparison with the simulation/experimental results.

## 1.1 Research Background

### 1.1.1 World population and material resources

In 2019, the United Nations Organization published a study on global world population growth, global life expectancy, and fertility levels[2]. It was found that the population grew steadily until 1900, at which time that were about 1 billion people. Since 1900 [3], the average life expectancy has increased, which led to a rapid increase in the total number of the world population from 1 billion to 7.7 billion. A look at the *Forecast on the development of the world population from 2015 to 2100* [4] shows that the rise will continue in the next 80 years (Figure 1), whereby a 10% increase is expected from 2019 to 2030 (from 7.7 billion to 8.5 billion), followed by a further 26% to 2050 (to 9.7 billion) and 42% to 2100 (to 10.9 billion) [4].

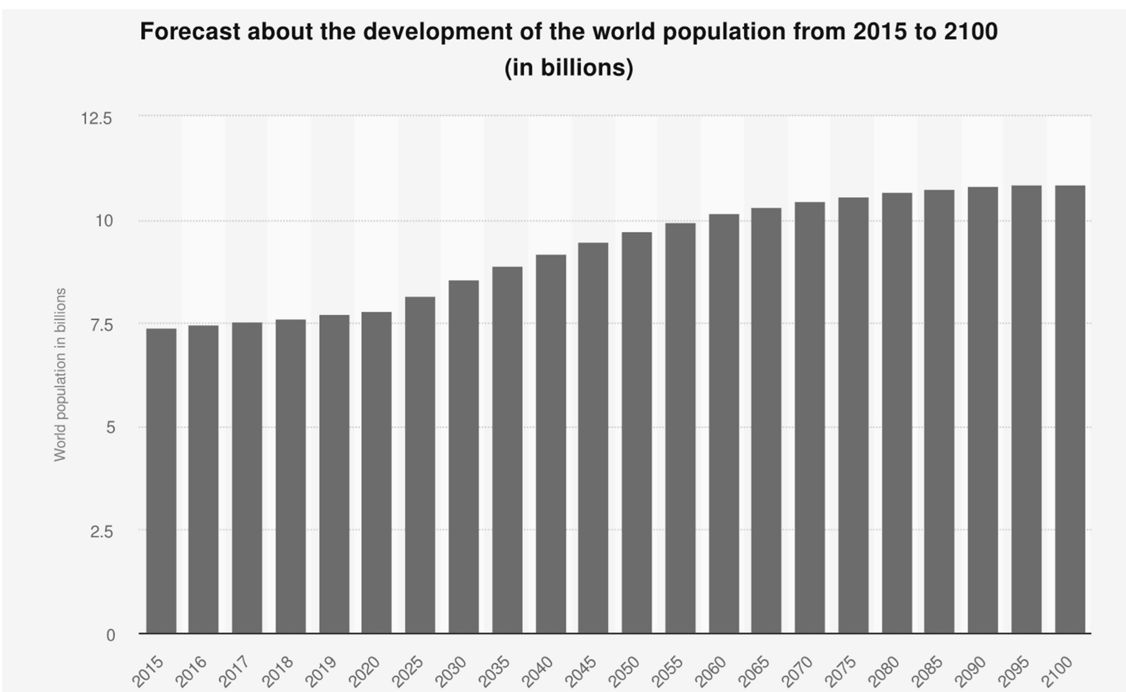



**Figure 1**. Forecast of the development of the world's population from 2015 to 2100 [4].

If projections of current patterns of population growth are sustained, so will demand for natural resources. Recent findings from the Global Footprint Network's study [5] of the difference between human demand for nature and nature's capacity show that humans are using natural resources as if they had 1.75 Earths at their disposal. Due to high demand, natural resources cannot regenerate properly, and the consequences of overexploitation of resources lead to loss of biodiversity, forests, and soils. The IPBES Global Assessment

Report on Biodiversity and Ecosystem Services found that "about 1 million animal and plant species are at risk of extinction" [6] within ten years. Since 1900, CO2 emissions have doubled, average global temperatures have risen, and one-quarter of terrestrial species have declined [6].

One of the indispensable building materials in Europe is gypsum. The gypsum industry in Europe has consumed about 100 million tonnes of FGD (flue gas desulfurization) in the last 25 years [7]. Germany alone consumed about seven million tonnes of FGD gypsum annually between 2000 and 2019 [8] and 22.9 million tonnes was consumed in the US in 2019 [9, 10]. However, with the expected shutdown of coal-fired power plants in Germany by 2035, FGD gypsum will no longer be available and 50% of the gypsum demand in Germany will be eliminated. This means not only an increase in natural gypsum mining but also in energy, costs, and CO2 release. The production of 1 tonne of natural gypsum releases about 140.7 kg of CO2 [11]. Several studies show that gypsum can be recycled or mixed with other complementary materials [11–13], ], although this is often too energy-consuming or recycling facilities are not available. New materials such as rattan or lime are also suitable for indoor use as gypsum, although no studies have considered salt (NaCl) as a substitute for gypsum. Therefore, in this work salt is proposed and a comprehensive understanding of the using salt indoor is expected.

### 1.1.2 Salt as by-product in industry

The world's seawater has varying surface salinity, measured in parts per thousand (per mil, ‰). The salt concentration in water is generally divided into three main groups: slightly saline water (1.0-3.0‰), moderately saline water (3.0-10.0‰), and highly saline water (10.0-35.0‰). Seawater belongs to the group of highly saline waters with about 35‰ or 3.5% [14]. This means that there are 35,000 parts of salt per million or 35 grammes of salt dissolved in one litre of water. The salinity of seawater mainly depends on the temperature of the water, and thus the salinity of seawater is highest near the equator and lowest near the North Pole [15]. For example, the Mediterranean Sea has a very high salinity due to the low connection with other seas, the low fresh water supply from the rivers and the high evaporation [16] (see Figure 2).

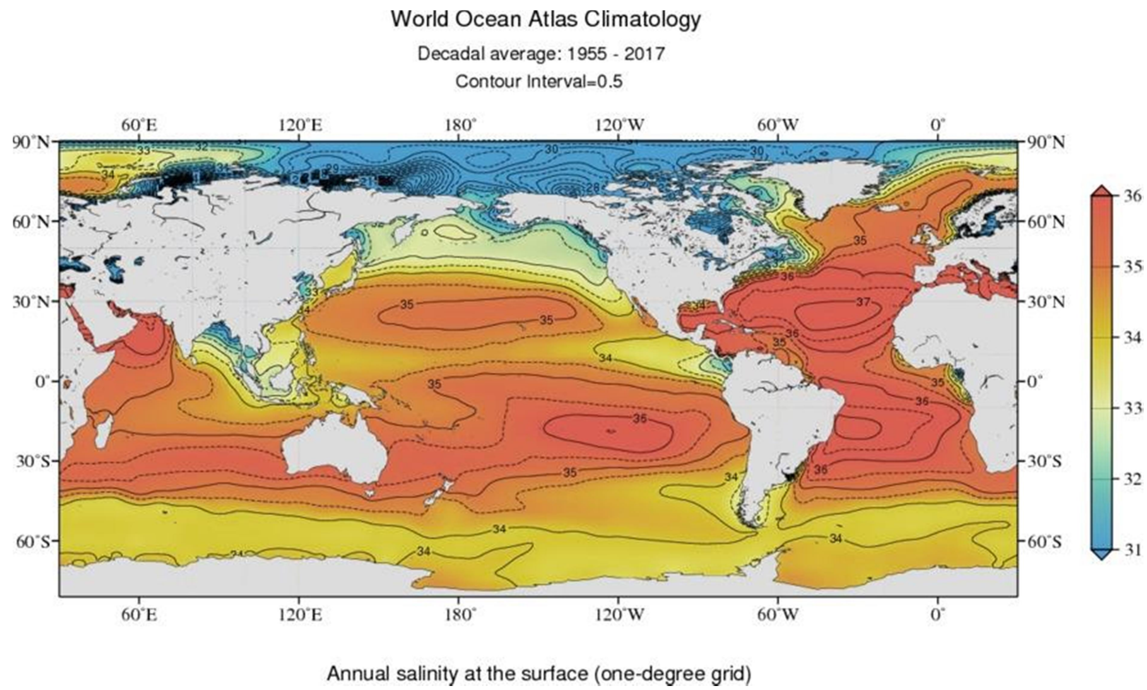



**Figure 2**. Annual seawater salinity at the surface [17].

Due to global population and economic growth, climate change, and water pollution, the demand for freshwater has increased [18, 19]. This problem leads to new solutions for obtaining freshwater such as desalination, rainwater harvesting, or wastewater reuse[18]. There are 15,906 operating desalination plants (Figure 3) worldwide, with 95 million m3/day of freshwater [20]. A major problem with unconventional water production is the discharge of about 141.5 million $m^3$ of brine (6.00% by weight is salt) per day into the sea [21]. The most common ionic compound is sodium chloride (NaCl), accounting for 85% of all constituents by weight [22]. In other words, about 8.45 million m3/day (3,098.85 million tonnes/year) of sodium chloride [20] is globally disposed into the sea. Nearly half of the salt disposed of in desalination plants (4.02 million m3/day) is produced in the Middle East and North Africa, followed by East Asia and the Pacific with 1.55 million m3/day and North America with 1.00 million m3/day (Table 1). Salt disposal is lower in Western Europe (0.77 million m3/day), Latin America and the Caribbean (0.48 million m3/day), Southern Asia (0.26 million m3/day), Eastern Europe and Central Asia (0.21 million m3/day), and Sub-Saharan Africa (0.16 million m3/day). The most salt disposal is produced by municipal sector use (62.3%) and industry (30.2%).

**Table 1.** Desalination plants [20] and salt disposal by region and sector use in the world.

| | Number of desalination plants | Desalination capacity | | Salt disposal from desalination plants million $m^3$/day |
|---|---|---|---|---|
| | | million $m^3$/day | Percentage of total % | |
| **GEOGRAPHIC REGION** | | | | |
| **Global** | 15,906 | 95.37 | 100 | 8.45 |
| **Middle East and North Africa** | 4826 | 45.32 | 47.5 | 4.02 |
| **East Asia and Pacific** | 3505 | 17.52 | 18.4 | 1.55 |
| **North America** | 2341 | 11.34 | 11.9 | 1.00 |
| **Western Europe** | 2337 | 8.75 | 9.2 | 0.77 |
| **Latin America and Caribbean** | 1373 | 5.46 | 5.7 | 0.48 |
| **Southern Asia** | 655 | 2.94 | 3.1 | 0.26 |
| **Eastern Europe and Central Asia** | 566 | 2.26 | 2.4 | 0.21 |
| **Sub-Saharan Africa** | 303 | 1.78 | 1.9 | 0.16 |
| **SECTOR USE** | | | | |
| **Municipal** | 6055 | 59.39 | 62.3 | 5.16 |
| **Industry** | 7757 | 28.80 | 30.2 | 2.55 |
| **Power** | 1096 | 4.56 | 4.8 | 0.40 |
| **Irrigation** | 395 | 1.69 | 1.8 | 0.15 |
| **Military** | 412 | 0.59 | 0.6 | 0.05 |
| **Other** | 191 | 0.90 | 0.4 | 0.04 |

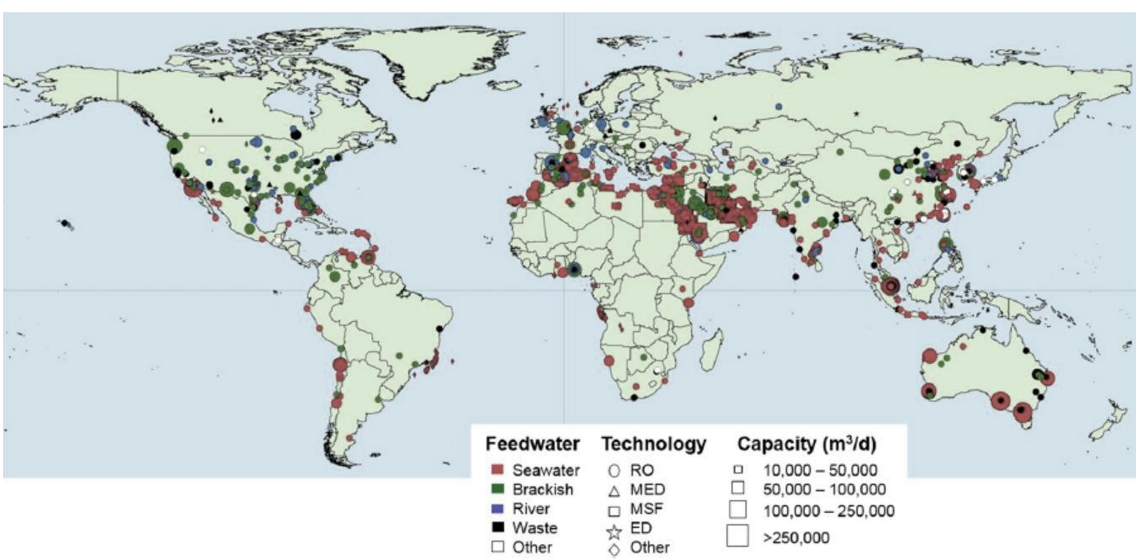



**Figure 3**. Global distribution of large desalination plants by capacity, feedwater type and desalination technology [20].

Even though the global brine disposal is not concentrated in a single area, the environmental impacts such as the loss of biodiversity in the marine environment and the increase of temperature and salinity are confirmed in many scientific studies [23–25]. The higher the salinity in brine, the slower the dilution between seawater and brine [26]. Most marine species have a very low tolerance to repeated salinity changes, which usually leads to a decline or – in the worst case – extinction of marine species. For corals, as little as 45 g/l (seawater has 35 g/l) is life threatening [25].

To ensure the growth of plants, various nutrients must be added to the soil, whereby one of these elements is potash. Potassium concentration varies from 63.2 wt % in sylvite to 16.9 wt % in carnalite minerals [27]. The rest of the minerals are halite (NaCl) and a 1-8% mixture of clay, silt, sand, and dolomite [28], which are considered mining wastes [29]. In 2018, the global potash production was 68.11 million tonnes/year [30]. If halite waste has between 36.8 wt% and 83.5 wt% of the mineral [31], then the amount of waste can be expected to be between 39.66 million tonnes per year (51,742.98 m3/day) and 336.527 million tonnes per year (439,043 m3/day). With 33.3% of the world's potash production (Table 2), Canada also has the most salt waste (minimum 13.21 to maximum 112.06 tonnes/year), followed by Belarus with 7.01 to 59.49 million tonnes/year, Russia with 6.84 to 58.05 million tonnes/year, and China with 6.84 to 58.05 million tonnes/year. All other countries together produce 6.84 - 58.05million tonnes/year.

Depending on the mining process, the waste is disposed of as salt mountains on the surface (Monte Kali in Germany, Figure 4) [27], injected/filled underground as brine, or discharged directly into rivers and seas [29]. The negative environmental impacts of salt mine waste have been investigated in numerous studies worldwide [32–34]. Braukmann and Boehme studied the chemical and biological characteristics of the Werra River in Germany due to nearby potash mining, finding that the salt-polluted sections are clearly due to salt pollution [32] and permanent recolonization by typical sensitive freshwater species is prevented [32]. The Llobregat Basin in Spain is another European region heavily affected by potash mining. A Freshwater Ecology and Management (FEM) research group studied the number of macroinvertebrate communities that decreased with increasing water conductivity [34]. The Potash Company in Saskatchewan potash mines in Canada also recognised that halite waste (NaCl) in small amounts is not hazardous to plants and aquatic life, although a high concentration is destructive to nature [28].

**Table 2.** World production of potash [30] and salt disposal from the potash industry.

| | World production of potash | | Salt disposal in million tonnes/year (min –max) |
|---|---|---|---|
| | in million tonnes/year | in percentage of total % | |
| **COUNTRY** | | | |
| **Global** | 68.11 | 100 | 39.66 – 336.52 |
| **Canada** | 22.68 | 33.3 | 13.21 – 112.06 |
| **Belarus** | 12.04 | 17.7 | 7.01 – 59.49 |
| **Russia** | 11.75 | 17.3 | 6.84 – 58.05 |
| **China** | 7.38 | 10.8 | 4.30 – 36.46 |
| **Other countries** | 14.26 | 20.9 | 8.30 – 70.46 |

If salt waste of 8.88 million $m^3$/day (0.008 $km^3$/day) from desalination and the potash industry were distributed over the entire Munich urban area (310.43 km2), in the worst case about 0.028 m (2,8cm) of the urban area would be covered in one day. Compared to plastic waste (300 million tonnes/year) [35], salt waste is almost 23 times higher at 6.806 billion tonnes/year (8.88 million m3/day). Salt waste is also three times higher compared to the estimated 2.22 billion tonnes of solid waste worldwide [36] in 2016.

The use of salt holds major potential not only for reducing pollution but also as a substitute for expensive and energy-consuming materials. Given the high global demand for cement (4.4 billion tonnes in 2021 [37]) and gypsum (306.6 million tonnes in 2020 [38]), it could be beneficial to blend salt with these materials. However, some potential uses for salt waste from desalination and the potash industry are rather limited. The use of salt waste from potash production could be straightforward since the salt is in powder form after the process. However, no current options have been found in the literature. The situation is different for desalination, since the brine contains little salt in the water. Here, it would make sense to pipe the brine to the salterns for evaporation, or use it for irrigation in agriculture, as in the Seawater Greenhouse project [39]. In this international project, the steam from the brine is used as a moisturiser for the growth of vegetables, and the rest is salt, which is not used. The United Arab Emirates pavilion (2 m x 5 m x 5 m) comprises a prototype made of environmentally friendly cement and brine from desalination plants. In this development of a more sustainable concrete, a salt compound (MgO) is used as a binder instead of cement [40]. Another architectural firm – Faulders Studio – [41] has developed a proposal for the design of a facade using brine from a desalination plant, which forms a translucent salt crust due to the evaporation of water. Another possibility of brine management is the production of NaCl for industrial purposes (production of plastics, glass, plastic, etc.) [42].

**Figure 4.** Monte Kali, Germany. Photo: Vesna Pungercar.

### 1.1.3 Hygrothermal performance of building materials

The use of new materials in construction not only means a solution to material shortages but also represents an opportunity to better understand new materials. Today, newly constructed or retrofitted buildings are expected to be energy-efficient [43], provide comfortable indoor living conditions [44] and be durable [45]. While new building codes improve energy efficiency through higher air tightness and better insulation of the building envelope, moisture issues seem to be a challenge and have already been recognised in many studies [46–49] and standards (EN ISO 13788, DIN 4108). The building envelope is an important layer between the outdoor climate and the indoor climate for hydrothermal performance. Excessive moisture in the building envelope or too high relative humidity in the indoor air provide good conditions for mould growth, material deterioration, and unsuitable indoor conditions for living.

For this reason, various computational and simulation methods have been carried out to predict thermal and moisture behaviour in construction. One of the first established models was determined in 1975 by Luikov [50], who described heat and mass transfer in capillary porous bodies using various thermodynamic and mechanical laws (Darcy's law, Fourier's law, Fick's law). A simplified calculation method (the steady-state dew point method) was proposed by Glaser and included in the German standard DIN 4108. However, due to its simplification for moisture content and condensation risk assessment, the method does not provide realistic results for building construction [49]. More realistic, complex, and widely used in research are heat, air, and moisture (HAM) models, which analyse in detail the heat, air, and moisture transport through the building envelope.

Many researchers [51–56] have used or developed HAM models for theoretical and experimental research of material properties, moisture and thermal performance in building construction, as well as for computational and simulation models. An example of computer implementation of the model HAM (Künzel equations) is the WUFI simulation programme [49]. The Künzel HAM model [57] describes moisture transport and heat transport in a material. Moisture transport is calculated with vapour moisture transport, liquid moisture transport and transport of the moisture that is already stored in the material.

Moisture transport within material according to Künzel [57, 58]:

$$\rho_l \frac{\partial u}{\partial \varphi} \cdot \frac{\partial \varphi}{\partial t} = \frac{\partial}{\partial x}\left(\rho_l D_l \frac{\partial u}{\partial \varphi} \frac{\partial \varphi}{\partial x}\right) + \frac{\partial}{\partial x}\left(\frac{\delta}{\mu} \frac{\partial p}{\partial x}\right)$$

[57, 58]

The left side of the moisture transport equation presents moisture storage of material (calculated with adsorption and desorption), while the right side presents liquid water transport (capillary conduction and surface diffusion) and vapour moisture transport.

Heat transport within material according to Künzel [57, 58]:

$$\frac{\partial H}{\partial \vartheta} \cdot \frac{\partial \vartheta}{\partial t} = \frac{\partial}{\partial x}\left(\lambda \frac{\partial \vartheta}{\partial x}\right) + h_v \frac{\partial}{\partial x}\left(\frac{\delta}{\mu} \frac{\partial p}{\partial x}\right)$$

[57, 58]

Heat transport is calculated with the latent heat effect and the heat storage. The left side of the equation presents the heat storage (heat capacity of the moisture and the dry material) and the right side presents the heat transport and latent heat effect (thermal conductivity and vapor enthalpy flow).

The choice of material depends on the available resources, climatic conditions and regulations of the country. They are used as a single layer or part of a multi-layer construction. In addition, the complexity of the wall construction and the materials chosen not only have an impact on the moisture content in the building structure but also the indoor air temperature, indoor humidity and energy consumption. Several studies in this area have largely focused on either the influence of materials on moisture content in building construction [44, 46, 48, 59], indoor temperature [60–62] or indoor humidity [63, 64] ], rather than conducting a comprehensive analysis of both simultaneously [65].

Therefore, when using a new material such as salt for indoor applications, understanding its influences on the thermal envelope and indoor living conditions holds strong importance. The material properties of salt (solubility, porosity, material structure, etc.) have already been discussed in the literature. Nevertheless, its applications in the thermal envelope under different climatic conditions, its hygrothermal influence and the future potential are still poorly understood.

## 1.2 Research objective and questions

This work aims to contribute to a better understanding of salt as a building material for the indoor application. To understand whether salt by-products from the desalination and potash industries can be used as a substitute material for gypsum, it must first be determined whether salt material can be used in construction at all. To evaluate such an objective, the three main research areas of the study arise:

**- Salt material:** Nowadays salt has a negative reputation in construction for corrosion risk and crystallization damages. Its advantages are still insufficiently studied and no review of all salt materials exists in the literature. Identifying different salt materials and structures might help to also see salt as a building material. The main aim of this part is therefore to identify which salt or salt composites have been already used as a building material in the past or developed within science and engineering that are the most appropriate for indoor applications. First, it is necessary to determine the material parameters of all salt materials and structure possibilities from a literature review. Second, the most suitable salt material for indoor has to be defined. The use of salt is limited to the interior due to the greater possibility of use (also possible in more inappropriate climate condition with the indoor heating, ventilation and condition). This salt material has to have the high amount of salt, having already been applied indoor, it must be available in the market and can be further analyzed at the Fraunhofer Institute for simulation and experimental studies.

**- Hygrothermal performance of salt and its influence on the indoor comfort.** Salt as a building material for interior application must take into account the risk of deliquescence. The hygrothermal consequences in building envelope by applying salt as an inner surface in different climate zones and the influence on the indoor air quality (indoor room temperature and relative humidity) and energy demand in the building therefore warrant close attention. This part of thesis should be able to show the hygrothermal behavior of salt in various climatic zones and under different indoor conditions (HVAC on, HVAC off) to ascertain the most suitable climatic/environmental conditions for the use of salt.

**- Application of salt with 3D printing:** Salt should be able to increase the resource efficiency of the building materials. 3D printing is one of the promising manufacturing techniques for salt, where no more commonly-used reinforcement with steel is required and a high amount of salt can be mixed with other materials. This part intends to show the possibility of using salt as an alternative material in additive manufacturing to increase resource efficiency and help to identify the potential binders and printing properties of salt printing mortar.

# 2 Research methodology

My work helps to fill the knowledge gap about the risks and benefits of using salt in the thermal envelope, which contributes to understanding the potential of salt as a building material. In order to achieve this goal, various areas must be linked. To accomplish this, I chose **a step-by-step approach** (Figure 5) of conducting a literature review (step 1), an exploration of hygrothermal performance (step 2), the application of salt in 3D printing (step 3), and evaluation results (step 4). In the first step, the most suitable salt material (availability in the market, high amount of salt, already applied indoor) is defined and its material properties are analyzed at Fraunhofer Institut IBS. In the second step, the hygrothermal performance of salt material from step 1 is investigated to determine whether salt can be used at all in the thermal envelope due to the risk of solubility. If this is the case, then the emerging construction technique (3D printing) is introduced to salt for higher resource efficiency of building materials and the possibility of non-steel reinforcement. At the end, all results are evaluated (step 4).

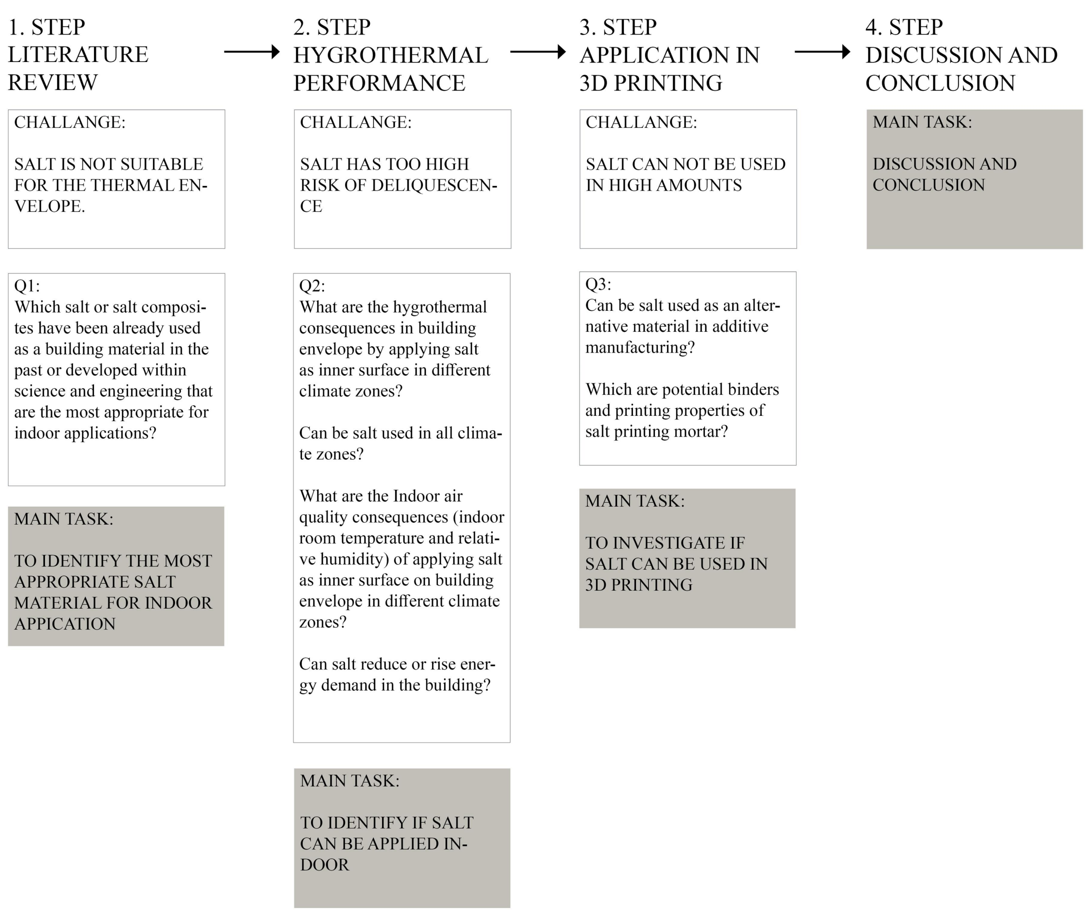



**Figure 5.** Methodology of the thesis in four steps. Scheme: Vesna Pungercar.

## 2.1 Step 1: Literature review

### 2.1.1 Scope

Current research on salt is mostly conducted from the perspective of chemistry or moisture damage in construction, and very few studies are related to its application and influence on the indoor environment in architecture. To answer the research question "What salt material has been used as a building material in the past or developed in science and technology that is best suited for interior applications?", a detailed literature review was conducted. The detailed state of the art is presented in chapter 5 (Appendix: Full texts of publications).

### 2.1.2 Method

The literature search is conducted on various databases (internet, library, government agencies and reputable organizations, patent databases). The literature on salt properties and building materials was published in English, German, Spanish and Slovenian. The keywords, titles and author names were searched in the databases in combinations of terms such as "Salt" AND "Building Material", "Salt" AND "Buildings", "Salt" AND "Architecture", "Salt" AND "Material Properties", "Salt" AND "Health" and other combinations. Most relevant articles were found in Scopus, Springer, Avery and MDPI. The literature review is organized into three groups with varying levels of detail, namely micro, meso, and macro (Figure 6). In the micro group, the material properties of salt (physical, chemical, mechanical) are studied. In the meso group, different salt materials in the building construction all around the world are presented. In the macro group, salt in building applications is analysed.

1. STEP LITERATURE REVIEW

| **MICRO** Properties of salt | **MESO** Salt materials | **MACRO** Salt structures |
|---|---|---|
| Salt classification<br>Salt cristillisation<br>Bulk density, porosity and permeability<br>Melting point, Specific Heat Capacity and Themal Conductivity<br>Solubility<br>Mechanical properties<br>Salt and health | Raw salt materials<br>Compose salt materials<br>Processed salt materials | Salt solid structure<br>Leyered structures with irregular or linear units<br>Shell structure<br>Mesh structures<br>Support structures |

**Figure 6.** Literature review in three-group framework. Scheme: Vesna Pungercar.

### 2.1.3 Results

At the micro level, different material properties of salt (Table 3) were found due to different formation history (geological or production process) and purity. The average bulk density of pure salt is mostly given in the safety data sheet of the pharma industry [66, 67] and is 2.165 g/cm³ at 25 ºC to 2.17 g/cm³ at 20 ºC. The typical bulk density value for rock salt deposits (halite) in nature is higher at between 2.16 g/cm³ and 2.25 g/cm³, due to the increased amount of impurities such as anhydrite, gypsum, dolomite, calcite, pyrite, quartz, and iron oxides [68]. The value of specific heat capacity of pure sodium chloride is between 0.853 J/(gK) [69] and 0.859 J/(gK) [70, 71]. With the small impurities, the value is higher (1.224 J/(gK) [68]). It is recommended to measure the value of thermal conductivity for pure sodium chloride at temperatures above 100 K and it is defined from 2 to 10 W/mK [71–73]. The most common value found for sodium chloride in the literature is from 6 to 6.5W/mK at room temperature [69, 72–75] and 3.3± 0.4 W/mK at 573 K [75]. Salt is soluble in water, methanol or formic acid, but not in ethanol or glycerol [69]. 36.0 g of pure sodium chloride 2.1s completely in 100g of water. In terms of material humidity, Feldman described NaCl as hydroscopic material with the critical point of solubility at 75.3% relative room humidity at 20ºC room temperature [69]. At more than 75.3% relative humidity, the pores in salt are filled with water, crystals start to dissolve and brine is formed [69]. The salt begins to dissolve and is no longer usable. This condition affects the durability of salt as a component of construction. Other threats of salt include salt-related problems in masonry and corrosion with steel. Therefore, for further studies the most appropriate salt material must minimize these risks.

**Table 3.** Properties of salt (NaCl) [76].

| Property | Value / Form | Literature |
|---|---|---|
| **Salt crystallization** | cubic shape | [77–80] |
| | pyramid shapes, hollow cubes or skeletal hopper | [77] |
| **Bulk density** | 2.165 g/cm³ at 25 | [66] |
| | 2.17 g/cm³ at 20 ºC | [67] |
| **Porosity** | lower than 3.8% (salt rock) | [70] |
| **Permeability** | less than $10^{-17}$ $m^2$ | [81, 82] |
| **Melting point** | 801 °C | [66, 83] |
| **Specific heat capacity** | 0.853 J/(gK) | [69] |
| | 0.859 J/(gK) | [70, 71] |
| | 1.224 J/(gK) | [68] |
| **Thermal conductivity** | 6 to 6.5 W/mK at room temperature | [69, 72–75] |

| | | |
|---|---|---|
| | 2 to 10 W/mK | [71–73] |
| **Solubility** | 75.3% relative room humidity at 20 ºC room temperature | [69] |
| **Health** | Speleotherapy (climate of salt caves) | [66, 84–90] |
| | Halotherapy (re-makes of climate of salt cave) | [85, 91–95] |
| | Climotherapy (Marine climate) | [96–98] |
| | Saline device (Sprays) | [85, 99–103] |

At the meso level, an investigation into different types of salt materials is shown at the level of a material product. The different types of salt were divided into three categories: raw salt, composite salt and processed salt. Raw salts are salts taken directly from nature without changing their chemical and physical properties and used in construction. Most historical examples are found in very hot and dry climates (Dallol, Ethiopia) [104], near salt lakes (Salar de Uyuni, Bolivia) [105], or near salt mines (Teghasa, Mali) [106]. They are also the salt materials with the highest salt content [76]. Composite salt materials are mixtures of salt and other materials. Composite salt materials in history and today have the same goal of improving porosity and strong bonding between two or more materials. These materials are Karshif salt block (salt and clay) [107], Roman seawater concrete (seawater and Roman concrete) [108], salt concrete (salt and modern concrete) [109], salt stucco (salt and natural rubber) [110] and salt-starch mixtures [111–113]. Processed salts are salt objects mixed with other additives and used in 3D printing, pressing or crystallization processes. To produce complex 3D structures, salt powder is used in binder jetting technology or paste extrusion. Compressed salt materials were first used in buildings as salt licks for animals with the waterproof protection [114]. The crystallization process was used to investigate objects such as salt plates [115] or shading systems for buildings [41]. In general, there are many salt materials, although very few have defined their physical, chemical and mechanical material properties at the same time (Table 4).

**Table 4.** Review of salt material properties [76].

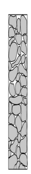
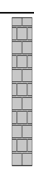
| Salt material | Bulk Density ($kg/m^3$) | Porosity (%) | Specific Heat Capacity (J/(K kg)) | Thermal Conductivity (W/(m·K)) | Water Vapor Diffusion Resistance Factor-dry 23°C, 50% RH) | Water vapour resistance factor "Wet" cup (µ value) | Moisture Buffering Value (M.-%) | Compressive strength (MPa) | Kinematics ductility (MPa) | Elastic modul (MPa) |
|---|---|---|---|---|---|---|---|---|---|---|
| **Pink Salt Rock [116, 117]** | 2162 | 3.50 | 865 | 2.650 | 1113-14559 | 10.3-1172 | 23.6* | | | |
| **Salt rock [70]** | 2130-2220 | 0.97-3.09 | | | | | | | | |
| **Salt rock [118]** | 2090-2160 | | | | | | | 17.1-22.3 | | |
| **Salt rock [119]** | | | | | | | | 12-32 | | |
| **Salt rock [75]** | 2160 | 1.00 | | 6.30± 0.60 | | | | | | |
| **Salt rock [68]** | 1920-2970 | 0.62-7.17 | 1.224 | 6.650 | | 0.00-3.24 | | 3.3-20.7 | | |
| **Karshif [120]** | 1970 | 21.29 | 710 | 1.62 | 15.77 | 3.11 | 12.3 | | | |
| **Old masonry karshif [121]** | 1550 ± 20 | 26±3 | | | | | | 9.74 | 2.10 | 774.63 |
| **New masonry karshif [121]** | 1540 ± 20 | 33±1 | | | | | | 2.66 | 3.67 | 347.17 |
| **Roman seawater concrete [122]** | 1390-1415 | | | | | | | 3.5-5.6 | | 3730-5160 |
| **Roman seawater concrete [123]** | 1542-2163 | | | | | | | 4.9-9.4 | | 4850-18800 |
| **Salt and starch [124]** | 1234 | | | | | | | 5.28 | | |
| **Salt and concrete [109]** | 1965 | 18.00 | 930 | 1.14 | | | | 24.1 | 2.50 | 25680 |
| **Salt and** | | | | | | 5.30- | | 35.5- | | |

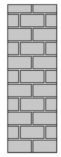
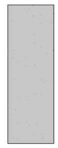
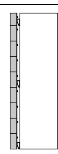
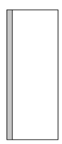
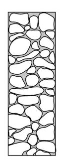
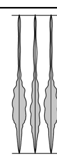
| | | | | | | |
|---|---|---|---|---|---|---|
| **concrete [125]** | | | | | 29.27 | 61.70* |
| **Concrete with seawater [126]** | | | | | | 56 - 83.5 |
| **Concrete with seawater[127]** | | | | | | 39.5-49.5 |
| **Salt concrete[128]** | 2080-2340 | | | | | 29.9-51.3 |
| **Salt concrete[129]** | | 10.50 | | | | |
| **Compressed Salt material [130]** | 1700-2300 | | | | | 40-86 |

*reviewed properties were tested at different conditions as in norms.

At the macro level, the existing possibilities of salt application in construction are analysed [76]. It is found that salt materials can be used in building as solid construction, as glued structures with irregular/linear units, or as salt objects or crystals incorporated into a shell, net, or load-bearing structure. For a load-bearing structure, a masonry method is usually used (salt blocks are bonded with a mortar), and for a non-load-bearing structure (cladding material) salt blocks are installed by gluing or fastening to the secondary structure. However, salt material application shows both advantages and limitations (Table 5).

**Table 5.** Advantages and limitations of salt material application [76].

| Structure | Material with % weight of salt | Shema | Advantages | (Possible) Limitations |
|---|---|---|---|---|
| **Interior wall** | Karshif salt block, ≥ 75% |  | - Simple technology<br>- Initial cost low<br>- Rough wall surface<br>- High fire protection | - Considerable handwork (local technique needed)<br>- Time consuming - salt stones have different shapes<br>- Available only in Siwa Oasis<br>- Poor mechanical properties<br>- Soluble in water |
| | Salt block from salt lakes, ≥ 95% |  | - High resource efficiency<br>- Smooth white surface<br>- Low pollutant emissions<br>- Integration of electric cables possible | - Application only possible in very dry, hot climate conditions<br>- Considerable handwork<br>- Possible to connect rectangular blocks with different mortar mixes |

| | | | | |
|---|---|---|---|---|
| **Exterior wall** | Salt block from salt lakes, ≥ 95% |  | - Humidity and temperature storage possible<br>- Natural white material<br>- Antibacterial | - Considerable handwork<br>- Walls have to be protected from water<br>- Walls are thicker, less sunlight can penetrate inside |
| | Salt concrete, ≥ 53% |  | - Easy to mix and to build with (no skilled craftswork)<br>- Good mechanical properties<br>- Higher resistency to water than other salt materials<br>- Salt waste can be used | - Build only in salt caves<br>- No other application known |
| **Wall covering (plaster, tiles)** | Salt block from mines, ≥ 84% |  | - Can be fixed with steel profiles, glued or hung on the mesh<br>- Factory prefabrication possible<br>- Damaged blocks can be replaced | - Very heavy elements<br>- Import from Pakistan<br>- Expensive<br>- No salt waste used<br>- Only for indoor applications |
| | Salt stucco, % not known |  | - For interior and exterior application<br>- Thin and wider layer possible | - Considerable handwork<br>- Combination with natural gum (rare and expensive) |
| **Seawater structures** | Roman seawater concrete, ≥ 0.2 |  | - Possible to build in seawater<br>- High mechanical properties<br>- High durability | - Other materials needed for a structure not easy available<br>- Very low salt content<br>- Much handwork<br>- Time consuming |
| **Temporary structures** | Salt and starch, ≥ 53% |  | - Additive manufacturing<br>- Time saving process<br>- Flexible design<br>- Thin structure | - Poor mechanical properties<br>- Referred to in the literature only as non-load-bearing structure<br>- Soluable in water, needs cpecial coating |
| | Crystalized salt, 100% |  | - Temporary structure (e.g.shading construction)<br>- Low Cost<br>- Indoor or outdoor application possible | - Low durability<br>- Application possible only in very dry, hot climate conditions near salt brine or salt lakes<br>- Soluble in water |
| **Interior floor** | Only salt, 100% | | - Easy to refill<br>- Cheap | - Difficult to clean<br>- Soluable in water |

Some studies have shown the extensive exploration of the material properties and provided insights into the hydrothermal performance of the material. The most promising salt material for indoor applications is ultimately selected based on several criteria. It is important that a salt material has already been used in construction, is suitable for the interior surface of the thermal envelope, has the highest salt content, and its hygrothermal properties can be defined. The most promising among the salt materials is Himalayan salt block (pink salt rock) with the highest salt content up to 98.30% [76], which is glued or fixed to the interior wall with the secondary structure [131] and is available in the market. This material is chosen for step 2 of this work. The material properties are defined at the Fraunhofer Institute for Building Physics IBP in Germany [116, 117] (see Table 2, Pink Salt Rock). The analyzed material properties are used as input for the simulation models in WUFI®Pro and WUFI®Plus.

### 2.1.4 Summary of Publication 1: Salt as a Building Material: Current Status and Future Opportunities

**Reference:**

V. Pungercar, F. Musso, "Salt as a building material: Current status and future opportunities," PLAN Journal : research in architecture and urbanism, vol. 6, pp. 393-413, 2021, doi:https://www.doi.org/10.15274/tpj.2021.06.02.4.

**Copyright:**

This peer-reviewed paper was originally published in THE PLAN Journal as open access, available at https://www.theplanjournal.com/article/salt-building-material-current-status-and-future-opportunities.

**The Indexing:**

The Avery Index, SCOPUS

**Summary:**

This publication represents the first step of a dissertation, exploring the current status and future opportunities for using salt as a building material. The reason for the use of salt in construction is the current shortage of material resources due to the growing world population and rising living standards. At the same time, a large amount of salt (NaCl) is produced as a by-product of desalination and potash production. However, most of it finds no further use, is disposed into nature and already causes environmental pollution. Therefore, the main objective of this work is to analyse the material properties of salt, identify different types of salt material used in construction in the past and show potentials for future use.

In the introductory part, challenges of salt such as salt contamination of flora and fauna in the production of desalination plants/potash industry and salt-related problems in masonry are presented. Furthermore, the properties of salt (crystallisation, bulk density, melting point, specific heat capacity, solubility and health problems) are compiled with literature references. The salt materials found in the literature are classified into three groups: raw salt materials, composite salt materials, and processed salt materials. Raw salt materials are salts taken directly from nature without altering their chemical and physical properties. Most historical examples are found in very hot and dry climates where no other local building materials are available. Composite salt materials are mixtures of salt and other materials. These materials are Karshif salt block (salt and clay), Roman seawater concrete (seawater and Roman concrete), salt concrete (salt and modern concrete), salt stucco (salt and natural rubber), and salt-starch mixtures. Processed salts are salt objects mixed with other additives and used in 3D printing, pressing or crystallisation processes. Salt was originally used as masonry, whereby salt blocks were joined with mortar to form exterior or interior walls. Later, with new material mixtures and manufacturing processes, new salt applications were added, including salt cladding, salt plaster, salt protection walls and temporary salt structures. In the near future, salt is expected to be used in additive manufacturing (3D printing).

This publication is the first-ever review of salt materials in construction and recommends future applications, including mixing salt with other materials to increase resource efficiency, hygrothermal analysis of salt materials, development of temporary structures (pavilions, exhibition structures, shading systems for buildings and open spaces), use as infill material for walls in dry and hot climates, or modification of salt with different construction techniques (3D printing, additive manufacturing, masonry, prefabrication).

**Declaration of own contribution:**

(VP: Vesna Pungercar; FM: Florian Musso)

Conceptualization, Methodology, Validation, Formal Analysis, Investigation, Resources, Data Curation, Writing—Original Draft, Preparation, Writing—Review and Editing, and Visualization was performed by VP (98.0%). Review was performed by FM (2.0%).

The overall own contribution of Vesna Pungercar for paper 1 (Salt as a Building Material: Current Status and Future Opportunities) is estimated at **98 %.**

## 2.2 Step 2: Hygrothermal performance and its influence on indoor air quality and energy demand

### 2.2.1 Experimental study

**Scope**

The aim of the experimental study is to investigate and validate the relationship between the hygrothermal behavior of the salt block and the microclimatic (real) conditions. Salt as an interior finish in the building envelope is subjected to different thermal and moisture transfer. These hygrothermal transfers depend on the properties of the salt and the real environmental conditions with unpredictable variations in humidity and temperature. Occupant behavior and density, ventilation, and building [132] all have an effect on indoor variations of RH and T fluctuations. As temperature increases and humidity decreases, the indoor material can be dried (the absorption capacity for water vapor increases). As temperature decreases and humidity increases, the material begins to absorb (water vapor is formed and absorbed) [53]. This cycle of drying - desorption (material shrinks) and absorption - adsorption (material expands) can cause stress, store excessive moisture in the material, or result in a loss of substance, which can cause damage over time [49]. In such an unpredictable environment, monitoring the stability of salt is even more important due to its critical hygrothermal conditions. Literature indicates that when the water content exceeds 0.5% (5 kg/m3) and the relative humidity exceeds 75.0%, salt starts to dissolve [69, 133]. The literature does not define whether real building scenarios with higher temperature and humidity variations are also critical, since most studies were conducted under controlled laboratory conditions. Ultimately, the experimental studies are compared with the simulation results to achieve a better validation of the salt. The main purpose of step 2 is to determine the hygrothermal performance and its influence on indoor air quality and energy demand of the salt block selected in step 1.

**Method**

No studies were found in the literature that investigated the hygrothermal performance of salt for application to interior surfaces by in-situ measurements. However, several researchers have investigated heat and moisture transfer in other porous materials using on-site measurements [134–136]. Latif et al. investigated the "hygrothermal behaviour of hemp and rock wool insulation materials in vapour-open wood frame wall panels" [136] (see Figure 7). Hansen et al. measured the hygrothermal conditions of internally insulated historic solid masonry walls [135], and Birjukovs et al. measured the temperature and RH monitoring of a hempcrete wall [134]. All research projects were similar in measuring temperature and humidity on different material surfaces of the thermal envelope to investigate different risks (mainly mould growth and corrosion). This method is also used in the present study. However, salt is antibacterial and mould growth is not a challenge. Therefore, a time of water content and RH above critical values is analysed to quantify the hygrothermal reactions of salt.

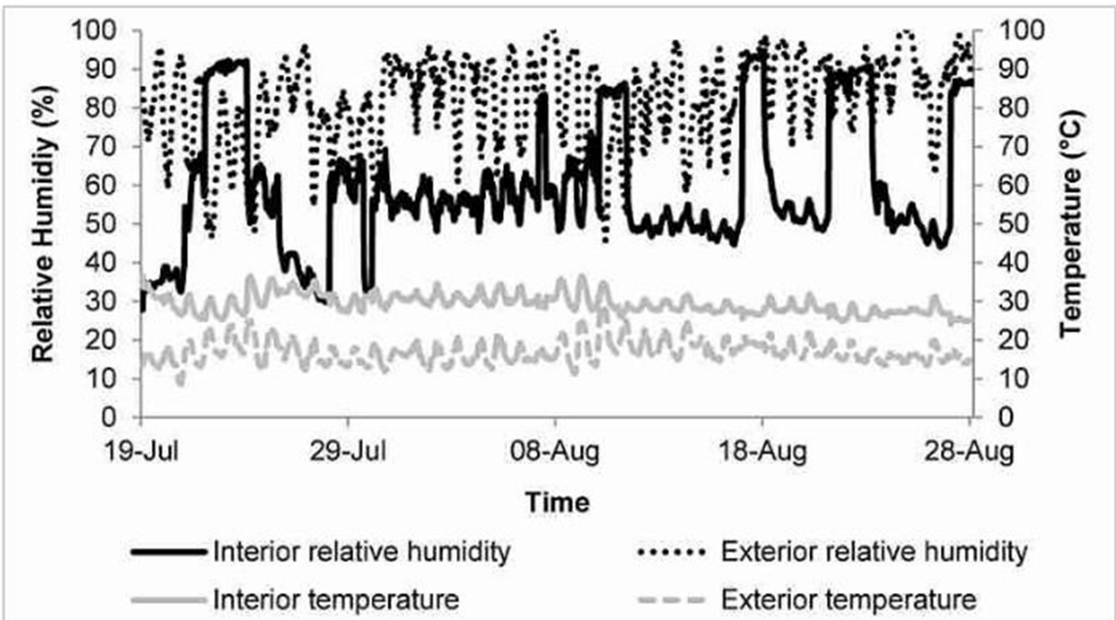



**Figure 7.** Measurement of the hygrothermal boundary condition in case of wood frame wall panels [136].

The experimental study is divided into three phases. In the first phase, three materials (pink rock salt, gypsum, and salt-gypsum) are selected as test materials (see Table 6). The Himalayan salt is a material that is compared with gypsum and salt-gypsum. The main reason for this comparison is to study the hygrothermal properties of salt and whether gypsum can be replaced. Gypsum is one of the most commonly-used materials for interior construction and it is an important component of today's construction industry worldwide. Salt-gypsum is a mixture of 30.0% salt and 70.0% gypsum that is still stable and can be used to perform compression tests. However, salt-gypsum is produced in the context of saving gypsum resources and has not been further tested. All materials are the same size (20 cm × 20 cm × 2.5 cm) and are fixed in a wooden frame with sealing tape (29.0 cm × 78.0 cm). It is assumed that the heat and moisture transfer is in the direction of the thickness of the material, so that only one surface is directly exposed to indoor environmental conditions.

**Table 6.** Summary of the hygrothermal properties of the applied materials.

| Material | NaCl content (%) | Density (kg/m$^3$) | Specific Heat Capacity (J/(K kg)) | Thermal Conductivity (W/(m·K)) | Water vapor diffusion resistance coefficient (μ) | | Compressive strength (MPa) | Flexural strength (MPa) |
|---|---|---|---|---|---|---|---|---|
| | | | | | dry | wet | | |
| **Pink rock salt** | 71,27-99.09a | 2162b | 1000 d | 2,650 b | 1113-14559 b | 10,3-1172 b | 33.7[c] | 5.73[c] |
| **Gypsum** | 0 | 1 500 [d] | 1000 [d] | 0,56 [d] | 10 [d] | 4 [d] | 4.10[c] | 1.40[c] |
| **Salt-gypsum** | 30[c] | - | - | - | - | - | | |

[a][70] [b] Fraunhofer Institute IBP in 2020 [c]mixed, examined at laboratory of TUM, Germany [d]DIN EN ISO 10456 [e]

The second phase is to install the test plate in the test room and measure the temperature and relative humidity. The test room is the children's room of the family of four in the flat in Munich, Germany. The indoor conditions are not controlled and vary due to the behaviour of the occupants, heating, natural ventilation and shading. The test panel is installed inside on the exterior wall of the room with sensors for temperature and relative humidity. Each test material has two sensors placed in the centre of the two surfaces: one facing the room and one facing the exterior wall. The indoor temperature and relative humidity are measured with one sensor in the centre of the room at a height of 1.8 metres. By placing the sensors on the surfaces of the test materials, critical conditions (deliquescence of the salt) are analysed and heat and moisture transfer are observed in a comparison between the materials (see Figure 8).

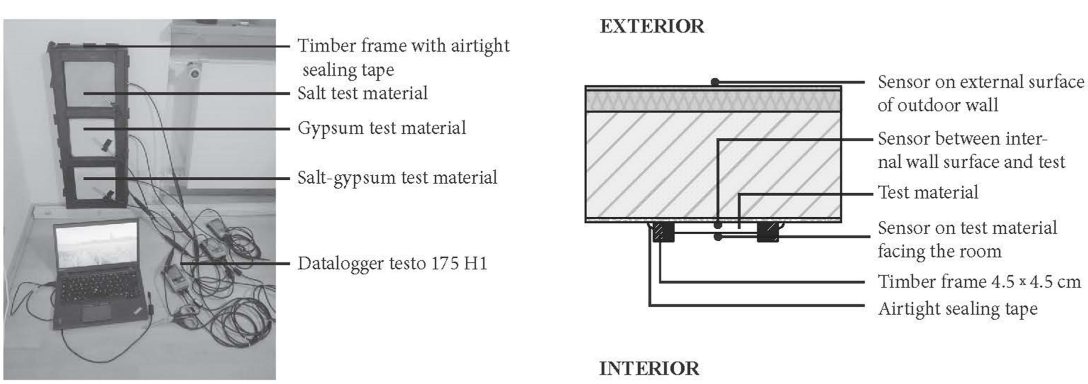



**Figure 8.** The test panel is installed in the testing room. Photo and drawing: Vesna Pungercar [137].

In the third phase, the measurement data are collected from the data loggers, organised using the Excel programme, and processed using the Origin programme.

**Results**

The results of the experimental study (see Table 7 and Figure 9) show that the measured average surface temperature and relative humidity of salt (S) are always slightly lower (up to 1.45°C in T and up to 4.21% in RH) compared to gypsum. The measured average surface temperature and relative humidity of the salt-gypsum (SG) are between the values of salt and gypsum.

**Table 7.** In-situ measurements of relative humidity (RH) and temperature (T) at the interior (In - looking at the interior) and exterior (Ext - looking at the exterior wall) surfaces of three materials (S—salt, G—gypsum, SG—salt-gypsum) [137].

| | S_In RH | S_In T | S_Ext RH | S_Ext T | G_In RH | G_In T | G_Ext RH | G_Ext T | SG_In RH | SG_In T | SG_Ext RH | SG_In T |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Min** | 33.46 | 18.90 | 33.31 | 18.40 | 39.93 | 18.91 | 41.24 | 18.57 | 41.97 | 18.84 | 38.17 | 18.57 |
| **Max** | 70.86 | 24.99 | 68.11 | 24.76 | 72.72 | 25.06 | 68.25 | 24.91 | 73.21 | 24.82 | 69.00 | 24.65 |
| **Ave** | 50.72 | 21.90 | 49.70 | 21.52 | 55.01 | 22.63 | 54.52 | 23.00 | 55.42 | 21.54 | 52.74 | 21.74 |
| **Mean** | 50.01 | 21.88 | 49.43 | 21.46 | 54.27 | 22.88 | 53.46 | 23.52 | 54.21 | 21.45 | 52.71 | 21.69 |

Internal and external temperature and relative humidity are shown in Figure 9. The fluctuations of the external environmental conditions are higher than those of the internal ones. Internal temperature is measured from min. 18.6°C to max. 26.9°C, external temperature from min. 0.2°C to max. 26.9°C, internal relative humidity from min. 21.4% to max. 83.3%, and external relative humidity from min. 21.4°C to max. 89.2%. Although the thermal envelope is not well insulated, the indoor relative humidity is high, mainly due to the fact that the testing room is directly connected to a bathroom.

It can also be observed that the values of average surface temperature and relative humidity of salt react more slowly compared to gypsum. All materials always react to the change of the internal environment. Comparing the interior (In - looking at the interior) and exterior (Ext - looking at the exterior wall) surfaces of each material, the average surface temperature and relative humidity remain more uniform in the interior.

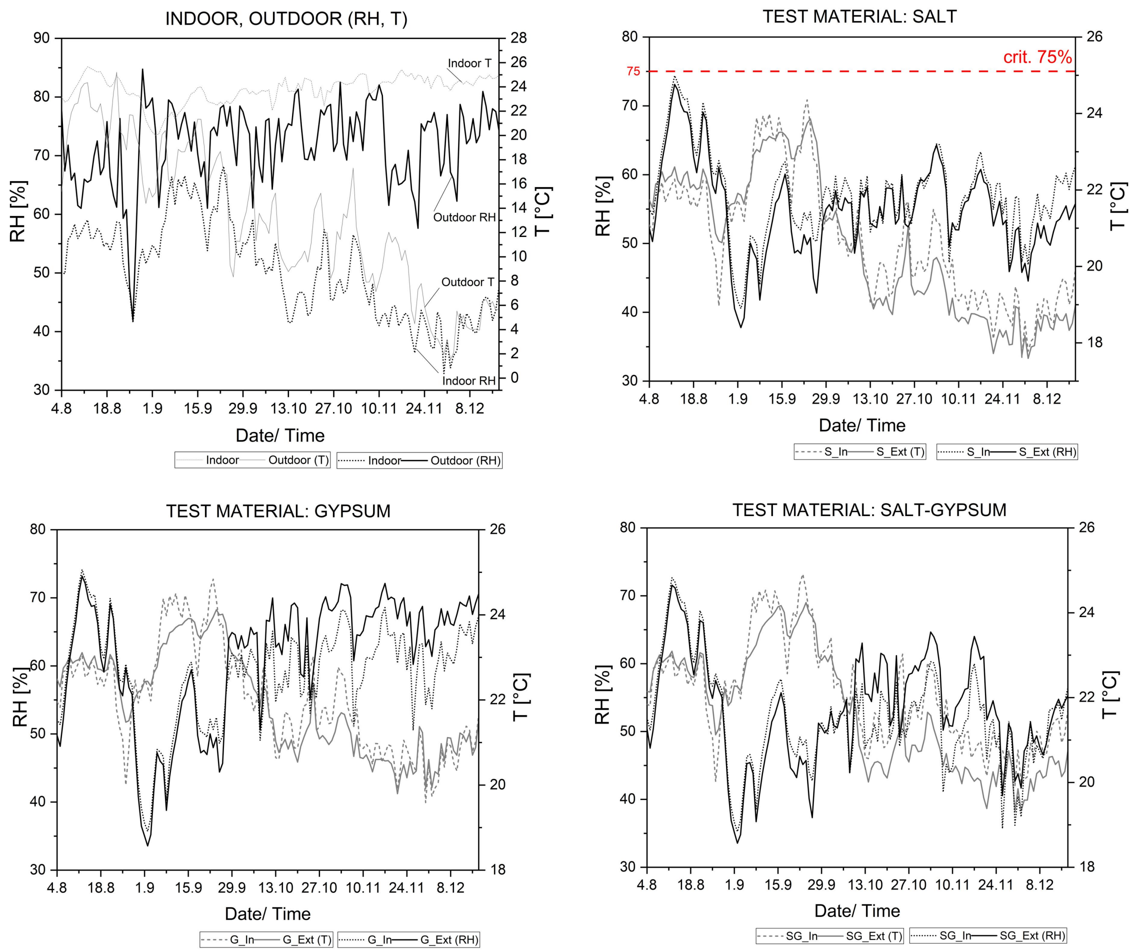



**Figure 9.** In-situ measurements of relative humidity (RH) and temperature (T) at the interior (In - looking at the interior) and exterior (Ext - looking at the exterior wall) surfaces of three materials (S—salt, G—gypsum, SG—salt-gypsum) and indoor/outdoor temperature and relative humidity.

## 2.2.2 Simulation study

### Scope

The simulation programmes WUFI®Pro and WUFI®Plus are used to perform hygrothermal processes in the building envelope for six different climatic conditions (tropical, arid, temperate, continental, Mediterranean and subpolar). WUFI®Pro is used to answer the following research question on the impact of salt on the building envelope: What are the hygrothermal effects on the building envelope of using salt as an interior surface in different climates? Can salt be used in all climate zones? WUFI®Plus is used to answer the following research question about the impact of salt on indoor comfort: What is the impact on indoor air quality (room temperature and relative humidity) of using salt as an interior coating for the building envelope in different climate zones? Can salt reduce or increase energy demand in the building? All simulations are performed with a comparison of gypsum and an analysis of whether there is potential to replace it with salt.

**Method**

Six cities in Europe and North America with different climate zones are selected as external conditions, four thermal envelopes (brick construction with variable size of thermal insulation due to countries' energy laws) are designed for WUFI®Pro/WUFI®Plus, and two different indoor conditions (with and without Heating, Ventilation and Air Conditioning - HVAC) are selected to simulate the hygrothermal performance of the thermal envelope, indoor air quality and energy demand (Figure 10). Ultimately, twelve simulations of WUFI®Pro (six cities with salt/gypsum application) and 24 simulations of WUFI®Plus (six cities with salt/gypsum application and with/without HVAC) are performed. In addition, the salt behaviour during climate fluctuations was investigated in the climate chamber to better understand the durability of the materials and possible damage potential.

Hygrothermal simulation is considered an important method to determine in advance the durability and hygrothermal behaviour of materials in different climatic zones. Different hygrothermal simulation tools (WUFI, DELPHIN, COMSOL, hygIRC, etc.) can be used to define advantages and disadvantages of materials and prevent critical hygrothermal situations such as mould growth. Several researchers investigated with WUFI®Programmes [47–49]. WUFI®Pro is used to investigate the hygrothermal behaviour of the thermal envelope. Chang et al. analysed "the hygrothermal behaviour of standard wood frame structures in Korea" [138], Hall et al. analysed the temperature profile evolution in stabilised rammed earth walls [139] and Zeng et al. [140] analysed the hygrothermal behaviour of composite thermal insulation systems. With WUFI®Plus, the hygrothermal performance of wall assemblies was not investigated, but rather their hygrothermal influences on the indoor climate. For example, Libralato et al. studied "multiyear weather data effects on hygrothermal building energy simulations"[141], Coelho et al. calibrated hygrothermal simulation models for historic buildings [142] and Allinson et al. analysed a stabilised rammed earth test building [143]. Since these and other studies provided realistic results and good agreement with simulated and measured data, WUFI®Pro and WUFI®Plus are used.

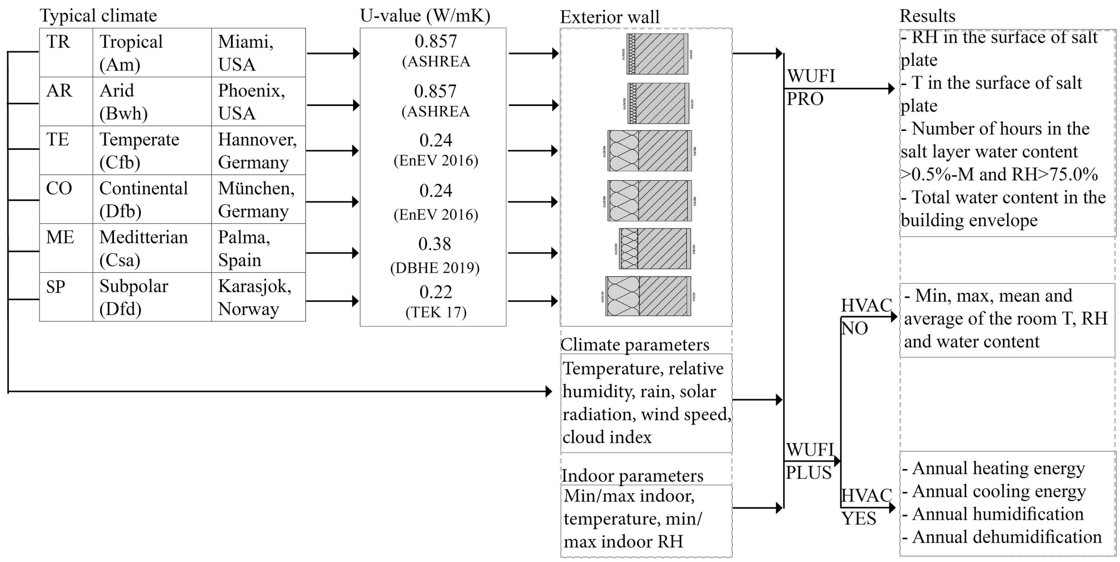
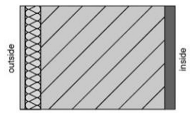
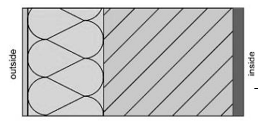
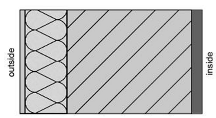
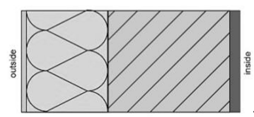



**Figure 10.** Simulation model design with the boundary conditions and expected results [137].

WUFI®Pro is used to study the temperature and humidity of each layer (salt or gypsum) and the influence of this material on the moisture transfer in the wall over time (three years) under six different climatic conditions (see Figure 10). When using salt as a material for interiors, the change in thermal and hygric values is calculated in comparison with gypsum. The two materials can be compared because they are porous materials that transport temperature and relative humidity in a similar way. The simulation with WUFI®Pro is performed to understand whether and in which climate zones the use of salt in indoor environments is possible. For the simulation with WUFI®Pro, the following conditions have to be defined: external conditions (climate parameters for tropical, arid, temperate, continental, Mediterranean and subpolar climates according to the Koeppen climate classification), internal conditions (indoor parameters defined by standards) and boundary conditions (hygric and thermal material properties of the individual material layers, standardized U-values of the wall structure). To determine temperature and humidity in salt and gypsum, respectively, the measuring devices were positioned close to the surface of the two materials. Most of the external, internal and boundary conditions (see Table 8) are predefined in WUFI®Pro and are set before starting the simulation calculation. For a more accurate simulation, a typical moisture content of the materials is assumed. The results of the calculated data were first converted as an Excel file into the Origin 2020 program for a more understandable graphical representation.

**Table 8.** Boundary condition (construction of the exterior walls with the material properties) used for WUFI®Pro and WUFI®Plus. The indoor material layer is gypsum or salt (dark grey) [137].

| | | | | Construction from Outside to Inside (cm) | | | |
|---|---|---|---|---|---|---|---|
| **Climate Zone** | | **U-Value ($W/m^2K$)** | **Mineral Plaster** | **Mineral Insulation Board** | **Solid Brick Masonry** | **Gypsum Plaster** | **Salt** |
| Wall 1: Tropical (TR) and Arid (AR) |   | 0.72 (gypsum) | 1.0 | 3.0 | 24.0 | 2.0 | |
| | | 0.77 (salt) | 1.0 | 3.0 | 24.0 | | 2.0 |
| Wall 2: Temperate (TE) and Continental (CO) |   | 0.23 (gypsum) | 1.0 | 14.0 | 24.0 | 2.0 | |
| | | 0.24 (salt) | 1.0 | 14.0 | 24.0 | | 2.0 |
| Wall 3: Mediterranean (ME) |   | 0.35 (gypsum) | 1.0 | 9.0 | 24.0 | 2.0 | |
| | | 0.35 (salt) | 1.0 | 9.0 | 24.0 | | 2.0 |
| Wall 4: Subpolar (SP) |   | 0.21 (gypsum) | 1.0 | 16.0 | 24.0 | 2.0 | |
| | | 0.22 (salt) | 1.0 | 16.0 | 24.0 | | 2.0 |
| **Material properties** | | | | | | | |
| Bulk density ($kg/m^3$) | | | 1900 | 15 | 1900 | 850 | 2087 |
| Porosity ($m^3/m^3$) | | | 0.24 | 0.95 | 0.24 | 0.65 | 0.04 |
| Specific Heat Capacity (J/kgK) | | | 850 | 1500 | 850 | 850 | 850 |
| Water Vapour Diffusion Resistance Factor (-) | | | 25 | 30 | 10 | 8.3 | 7836 |
| Thermal conductivity (W/mK) | | | 0.8 | 0.04 | 0.6 | 0.2 | 2.65 |
| Typical Build-In Moisture ($kg/m^3$) | | | 210 | 44.8 | 100 | 400 | 999 |

The heat and moisture process simulation in WUFI®Plus evaluated the impact of the meteorological data and material parameters on the indoor air conditions and calculated the energy demand. With WUFI®Plus, the influence of salt on the indoor air quality in six different climate zones was investigated. The external (climate parameters for tropical, arid, temperate, continental, meditterian and subpolar climate zones) and boundary conditions (hygric and thermal material properties of individual material layers, normed u-values of the wall assembly) remained the same as in WUFI®Pro (see Table 9). However, the study object was no longer a thermal envelope, but a room of 3.0 m × 3.0 m × 3.0 m with and without heating, ventilation and air conditioning (HVAC). Salt or gypsum was set as the indoor surface of each exterior wall to analyse heat and moisture exchange. The room had no windows and the floor and the ceiling had the same interior conditions to avoid additional heat or moisture load. For each climate zone, four different simulations were conducted: salt interior surface with and without HVAC and gypsum interior surface with and without HVAC. First, the HVAC was turned off to analyse the indoor air quality (temperature and relative humidity) and later it was turned on to calculate the annual energy demand (heating, cooling, humidification and dehumidification).

**Table 9.** Outdoor and indoor condition for simulation model in WUFI®Pro and WUFI®Plus [137].

| | **WUFI®Pro** | **WUFI®Plus** |
|---|---|---|
| **Outdoor condition (weather data)** | Real weather data from the WUFI®Pro/Plus programme | Real weather data from the WUFI®Pro/Plus programme |
| **Indoor condition** | USA: ASHRAE 160<br>Europe: EN 15026, DIN 4108, WTA 6-2 | USA: ASHRAE 160<br>Europe: EN 15026, DIN 4108, WTA 6-2 |
| **Component (wall/room)** | Thermal envelope | Room (3 m × 3 m × 3 m) |
| **Calculation Period, Profiles** | Three years<br>(time steps: 1 h) | One year<br>(time steps: 1 h) |
| **Orientation** | Wall component is oriented to north (the lowest solar radiation) | No windows to evaluate the influence of the climate zones and construction |
| **Inclination** | 90° | 90° |
| **Initial moisture and temperature in construction component** | RH = 70.0%<br>T = 20 °C | RH = 70.0%<br>T = 20 °C |
| **Driving Rain Coefficients** | 0.07 | 0.07 |
| **Monitor Position** | Material surface | In a room |
| **Number of occupants** | 1 person per room | 1 person per room |
| **Office indoor heat and moisture load** | Standard program input | Convective heat: 33.3 W<br>Radiant heat: 25.2 W,<br>Moisture 17.55 g/h,<br>$CO_2$: 20.79 g/h<br>Human activity: 1.2 met<br>Air velocity: 0.1 m/s |
| **Clothing** | Standard program input | 0.7 clo |
| **Occupancy Period** | Standard program input | 7.00–18.00 |
| **Energy system** | Only heating<br>Depending on the climate zone (norms: EN 15026, DIN 4108, WTA 6-2, ASHRAE 160) | HVAC on:<br>Indoor air temperature 21–27 °C<br>RH 40.0–70.0%<br>Max $CO_2$: 3000 ppmv |

| | |
|---|---|
| | Air exchange: 0.6 $h^{-1}$<br>Heating, cooling, humidification, and dehumidification calculated<br>HVAC off |

**Results**

The WUFI®Pro study shows that salt is not suitable for humid climates with low U-value thermal envelope requirements. In tropical (see Figure 11, TR_S_RH) and Mediterranean climates (see Figure 11, ME_S_RH), a risk of salt deliquescence is simulated (the critic value is exceeded). In temperate, continental and subpolar climates, there is no risk due to high thermal envelope and indoor air quality requirements. Values of surface relative humidity of salt are almost the same in comparison to gypsum. It is also observed that gypsum is more responsive to environmental changes in relative humidity (higher fluctuations).

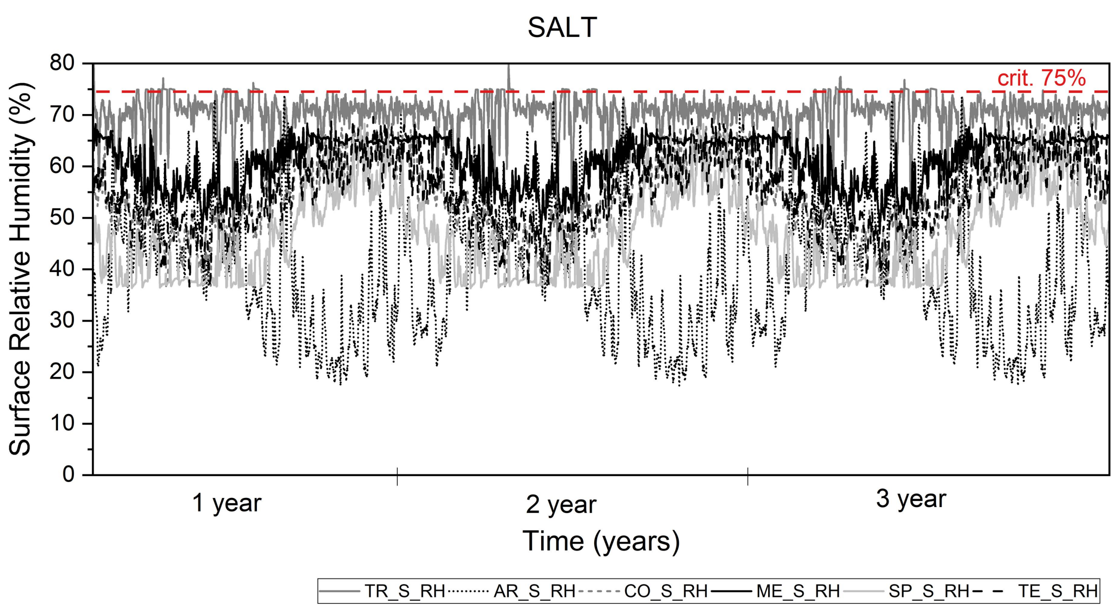



**Figure 11.** Simulated RH of salt over three years (G_ RH - gypsum and relative humidity, S_ RH - salt and relative humidity) in six different climatic conditions (TR - tropical, AR - arid, CO - continental, ME - Mediterranean, SP - subpolar, TE - temperate).

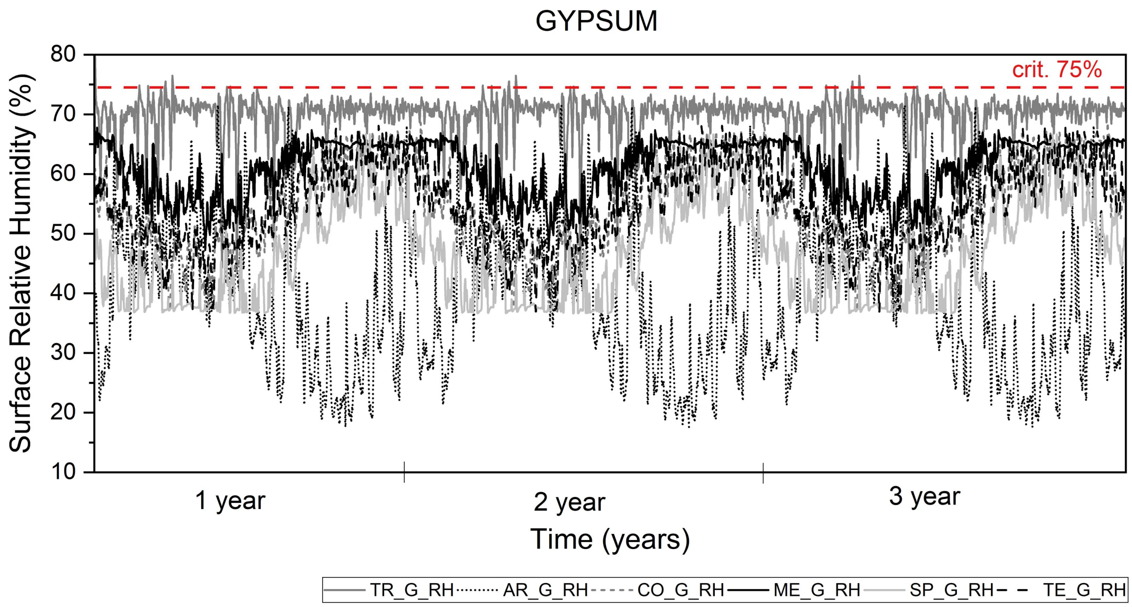



**Figure 12.** Simulated RH of gypsum over three years (G_ RH - gypsum and relative humidity, S_ RH - salt and relative humidity) in six different climatic conditions (TR - tropical, AR - arid, CO - continental, ME - Mediterranean, SP - subpolar, TE - temperate).

The best outdoor conditions for salt are in dry climates, although the thermal envelope has a high U-value (see Figure 11, AR_S_RH and Figure 13, AR_S_WC). However, the average surface water content is higher for salt because salt cannot transport moisture as quickly as gypsum (see Figure 13). Figure 13 shows the highest values of water content in tropical and Mediterranean climates in salt material (where the critical values are above the red line).

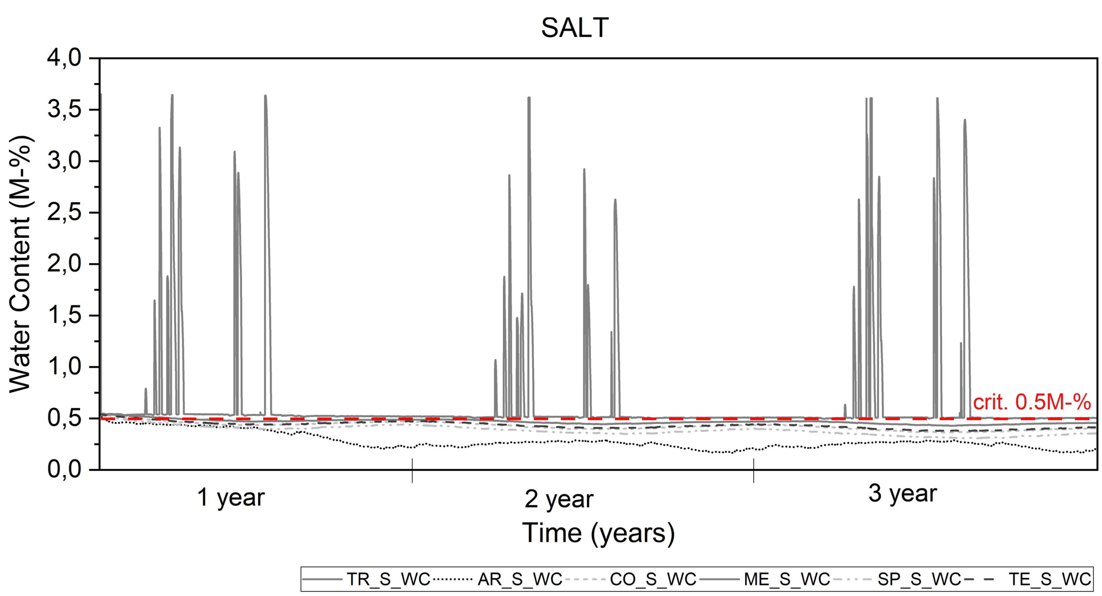



**Figure 13.** Simulated water content of salt over three years (G_ WC - gypsum and water content, S_ WC - salt and water content) in six different climatic conditions (TR - tropical, AR - arid, CO - continental, ME - Mediterranean, SP - subpolar, TE - temperate).

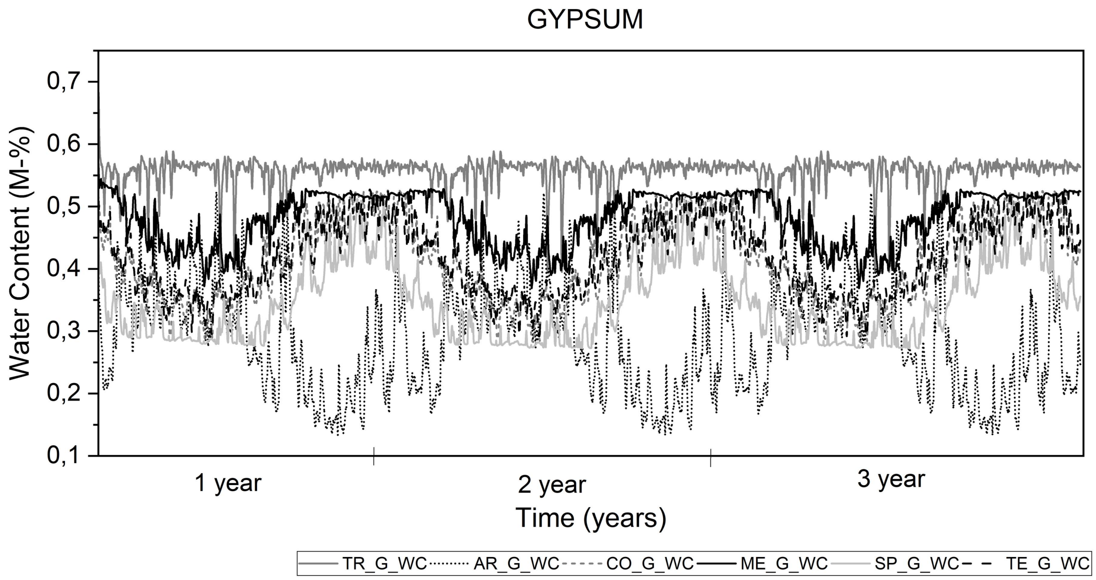
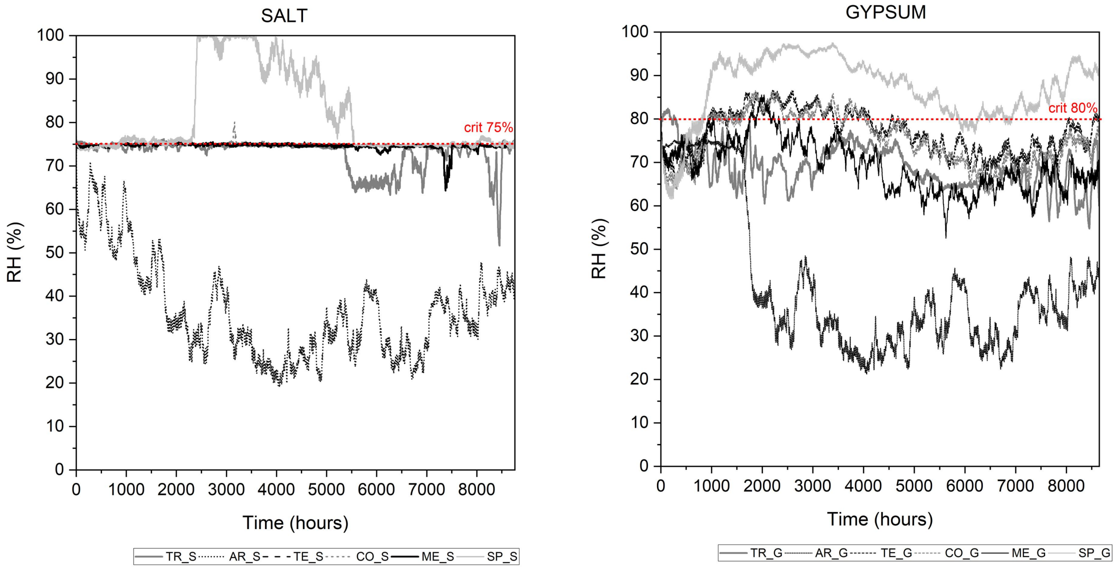



**Figure 14.** Simulated water content of gypsum over three years (G_ WC - gypsum and water content, S_ WC - salt and water content) in six different climatic conditions (TR - tropical, AR - arid, CO - continental, ME - Mediterranean, SP - subpolar, TE - temperate).

The results of WUFI®Plus support those of WUFI®Pro. Simulation models without HVAC show that an airtight thermal envelope with salt results in indoor air RH of more than 75% in five out of six climate zones (see Table 10). Moreover, for simulation models without HVAC for thermal envelope with gypsum air RH is higher than 80% in five out of six climate zones, which presents a higher risk of mould growth [49, 53]. In general, indoor temperature is lower without HVAC for both materials in colder climate zones and higher in hot climate zones. However, in most of the climate zones indoor temperature is lower with salt than with gypsum. This means that salt application without HVAC or without indoor air quality compliance is only possible in dry and hot climates.

**Table 10.** Simulated indoor temperature and relative humidity of salt and gypsum over 1 year without Heating, Ventilation and Conditioning (G- gypsum, S - salt) in six different climatic conditions (TR - tropical, AR - arid, CO - continental, ME - Mediterranean, SP - subpolar, TE - temperate) [137].

| | **TR_G** | **TR_S** | **AR_G** | **AR_S** | **TE_G** | **TE_S** | **CO_G** | **CO_S** | **ME_G** | **ME_S** | **SP_G** | **SP_S** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | **Indoor Relative Humidity (%)** | | | | | | |
| Min | 54.75 | 51.64 | 21.25 | 19.22 | 63.63 | 73.95 | 62.42 | 73.95 | 52.54 | 64.30 | 61.52 | 73.34 |
| Max | 82.38 | 76.19 | 75.47 | 73.87 | 86.58 | 76.68 | 86.48 | 80.12 | 85.51 | 75.94 | 97.57 | 100.00 |
| Ave | 69.01 | 72.93 | 41.93 | 36.45 | 76.91 | 74.85 | 75.31 | 74.86 | 69.39 | 74.55 | 87.13 | 81.56 |
| Mean | 68.63 | 74.43 | 36.72 | 34.14 | 76.91 | 74.86 | 75.31 | 74.83 | 68.75 | 74.69 | 89.22 | 75.57 |




| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Indoor Air Temperature** | | | | | | | | | | | | |
| Min | 17.18 | 17.07 | 11.83 | 11.82 | 4.38 | 5.14 | 2.57 | 3.48 | 10.14 | 10.24 | -1176 | 10,24 |
| Max | 31.98 | 31.82 | 39.08 | 39.46 | 21.34 | 21.16 | 21.90 | 21.66 | 29.85 | 29.11 | 19.83 | 29.10 |
| Ave | 25.81 | 25.68 | 26.73 | 26.93 | 12.98 | 13.09 | 12.58 | 12.66 | 20.08 | 19.85 | 7.38 | 19.85 |
| Mean | 26.93 | 26.72 | 27.40 | 27.57 | 13.13 | 13.30 | 12.11 | 12.34 | 19.57 | 19.38 | 7.16 | 19.38 |

With HVAC, indoor conditions are controlled and the application of salt is broader. However, salt can transport heat faster (thermal conductivity is higher) and moisture slower (water vapour permeability is lower). Therefore, the cooling, heating, and dehumidification requirements are somewhat slightly higher with salt than with gypsum. Nevertheless, salt has advantages in very hot and dry climates where the indoor surface temperature of the material is lower and an indoor RH is reduced by rapid drying. The reduction in RH loss through the thermal envelope in very hot, dry ambient conditions is perceived to be more comfortable (see Figure 15).

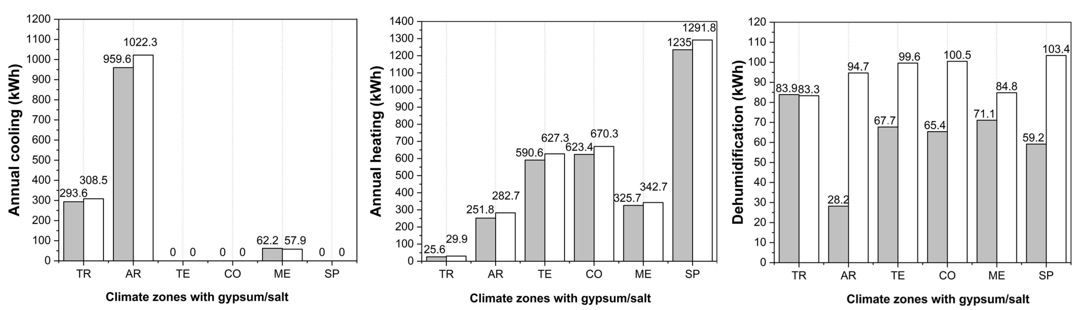



**Figure 15.** Comparison of annual cooling, heating, and dehumidification demand for gypsum and salt in six climate zones (TR—Tropical, AR—Arid, TE—Temperate, CO—Continental, ME—Mediterranean, SP—Subpolar, grey—gypsum, white—salt) [137].

### 2.2.3 Summary of Publication 2: Hygrothermal Performance of Salt (NaCl) for Internal Surface Applications in the Building Envelope

**Reference**

V. Pungercar, F. Musso, "Hygrothermal Performance of Salt (NaCl) for Internal Surface Applications in the Building Envelope," Materials, vol. 15, no. 9: 3266, 2022, doi: https://doi.org/10.3390/ma15093266

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**Summary**

This publication presents the second step of the dissertation: "Hygrothermal Performance of Salt (NaCl) for Internal Surface Applications in the Building Envelope". The main motivation for this work is to study the hygrothermal influence of salt on building construction, indoor climate and energy consumption under six climatic conditions (tropical, arid, temperate, continental, Mediterranean, subpolar). To achieve this goal, hygrothermal simulations (WUFI®Pro, WUFI®Plus) and experimental measurements are performed. The test salt material is Himalayan salt, which is analysed at the Fraunhofer Institut IBP and serves as an input for both studies. For better understanding, the salt material is always compared with gypsum.

WUFI®Pro is used to study the temperature and humidity of the individual layers (salt or gypsum) and the influence of this material on the moisture transfer in the wall over time (three years). Compared to gypsum, the temperature and relative humidity values of salt do not change as dramatically with the change in air RH or T, and the water content throughout the building envelope is slightly higher in the thermal envelope with salt due to its lower water vapour permeabilit. WUFI®Plus was used to study the effect of salt on indoor air quality (temperature and relative humidity) and energy consumption (cooling, heating, dehumidification, humidification) with and without HVAC in six climate zones. Without HVAC, the application of salt is only possible in arid (hot and dry) climates. With HVAC and the airtight thermal envelope, salt application is possible in three other climate zones (temperate, subpolar, and continental). Salt can transport heat faster and moisture slower than gypsum. Therefore, salt simulates a slightly higher cooling, heating and dehumidification demand. Nonetheless, the reduction in RH loss due to the thermal envelope and the lower interior surface temperature due to salt is perceived to be more comfortable in arid climates. The experimental study measures the average surface temperature and relative humidity of three test materials (salt - S, gypsum - G, salt-gypsum - SG) under real conditions for five months. The results show that the average surface temperature and relative humidity are always slightly lower for salt than for gypsum. The measured average surface temperature and relative humidity of salt-gypsum (SG) are between the values of salt and gypsum. At the end, the experimental results are compared with the simulation results, which are confirmed accordingly.

The results of simulation and in-situ measurements show the potential of salt for indoor surface applications in building envelope without HVAC in very dry and hot outdoor conditions and could be considered with HVAC and airtight thermal envelope in temperate, subpolar and continental climates.

**Declaration of own contribution:**

(VP: Vesna Pungercar; FM: Florian Musso)

Conceptualization, Methodology, Software, Validation, Formal Analysis, Investigation, Resources, Data Curation, Writing—Original Draft Preparation, Writing—Review and Editing, and Visualization was performed by VP (98.0%). Review and Conceptualisation was performed by FM (2.0%).

The overall own contribution of Vesna Pungercar for Paper 2 (Hygrothermal Performance of Salt (NaCl) for Internal Surface Applications in the Building Envelope) is estimated at **98 %.**

## 2.3 Step 3: Application of salt in 3D printing

### 2.3.1 Scope

In the first step, it will be shown that salt has already been used in construction, while in the second step it will be highlighted that salt can be used in the thermal envelope despite the high risk of salt deliquescence. The third step is to investigate whether it is possible in the future to use salt together with other materials in 3D printing technology (paste extrusion) to open up new markets in the construction industry and increase the resource efficiency of the printing mortar by increasing the salt content. The material goals (highest possible salt content in salt printing paste, good printing properties and a desired shape) and technology goals (speed, cost, accessibility) make salt more resource-efficient and environmentally friendly as a material, and give it a new function. Salt is porous, can be bonded, and has already been used in some additive manufacturing processes. The most common 3D printing method that has been used with salt is binder jetting [111–113, 144], whereby salt is first deposited as a thin layer on a surface and bonded by a binder. These first two steps are repeated several times [145]. The 3D printing method presented in this paper is paste extrusion, in which different materials are mixed and pushed through a nozzle of the 3D printer to create an object by applying a layer of the paste from the bottom up [146].

### 2.3.2 Method

Before 3D printing began, various salt mixtures (salt and starch, salt and gypsum, salt and clay) were studied to determine whether salt could combine with other binders at all. Further information can be found in chapter 7 Appendix C: Material mixtures. After ascertaining that salt can bond with other materials, the 3D printing study began.

The salt printing mortar is mixed, printed on a small scale, and evaluated for future 3D printing on a larger scale (see Figure 16). All printed objects are created using Potter Bot Micro 10 at the Chair of Design, Construction and Materials (EBB) at the Technical University of Munich. The investigation is conducted in three phases. In the first phase, the mixing ratio of salt and binders (clay, Portland cement, quartz sand, starch, water and gypsum) is defined by continuously improving the quality of the printed objects. Four different groups of materials (SS - salt and starch, SC - salt and clay, CS - salt and concrete and SG - salt and gypsum) were studied, each with six different formulation. Each formulation is printed experimentally and evaluated by printability criteria found in literature (consistency of the printed form, pumpability, adequate bonding time, acceptability for building another layer and smoothness of the surface) [83]. In the second phase, the most promising salt mortar from the first phase (salt and clay) is modified by using different additives (starch and fine fibres of straw). Starch is used to change viscosity and control the efflorescence. Fibres of straw is used as a natural reinforcement to increase structural stability. At the end, four cylinders (C -clay, CS - salt-clay, CSS - salt-clay-straw and SSC - salt-starch-clay) with the size of 10.0 x 10.0 x 10.0 cm are analysed by 3D scan [147] and visual evaluation (pumpability, printed shape maintenance, proper binding time, possibility to build up another layer and surface smoothness). 3D scanner Keyence VL measures the size discrepancies (deformations) of all four 3D cylinders in comparison to the original geometry of the 3D model. In the third phase, salt mixtures in 3D extrusion processes are analysed in two master courses together with students (winter semester 2020 and summer semester 2021) at the Chair of Design, Construction and Materials (EBB) at the Technical University of Munich for different applications in the building construction and printed on a small scale. More detailed information can be found in chapter 5 (Appendix A: Full texts of the publications).

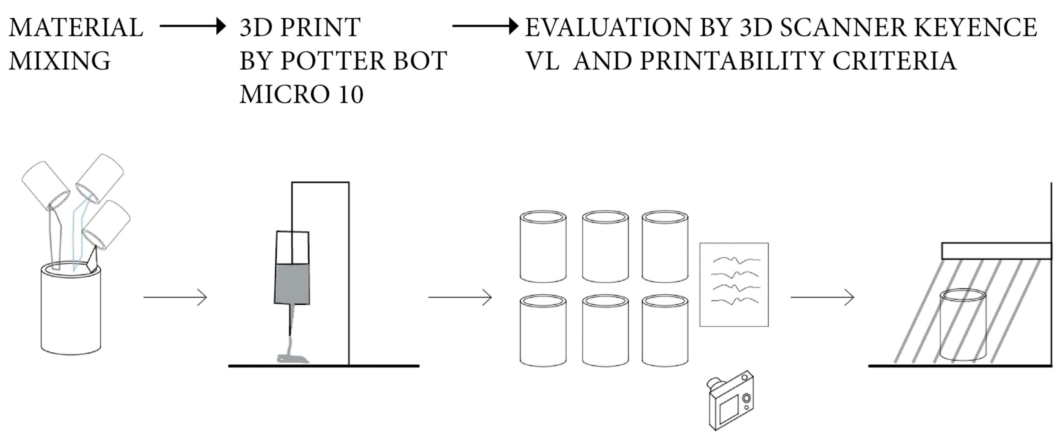


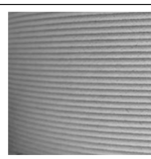
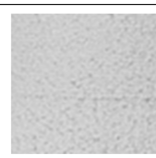
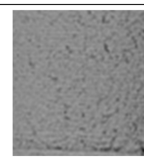
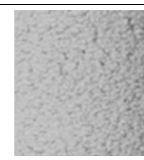
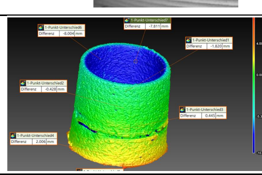
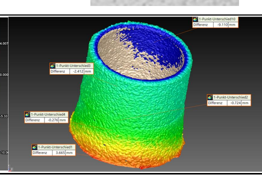
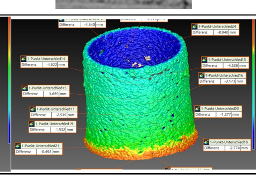
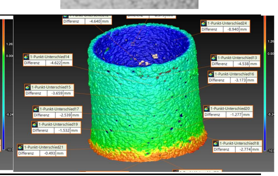

**Figure 16.** Methodology of 3D printing with salt mortar. Scheme: Vesna Pungercar [148].

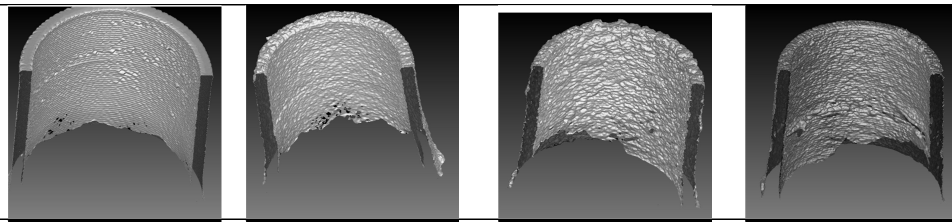
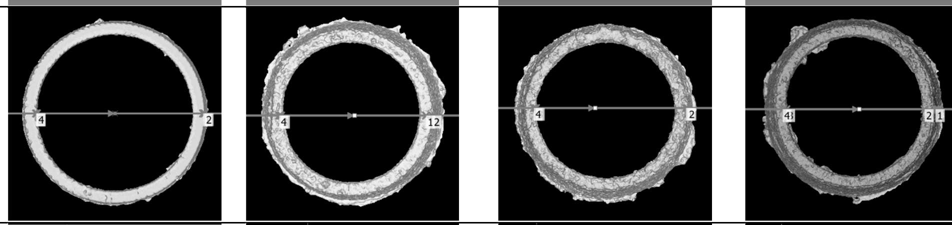
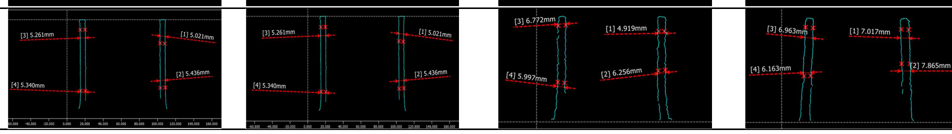
### 2.3.3 Results

The results of a small-scale 3D printing with salt show that it is possible to use the paste extrusion process. It was found that the mortar needs to be adapted to the printer itself and for large-scale printing the mortar probably needs to be modified. Table 11 shows the comparison between the four 3D-printed cylinders, using the clay cylinder as a reference. It was found that all cylinders have some deformations and did not maintain the height of 10 cm after the

3D printing and drying process, the printing layer width and the surface. The color gradation of the 3D scans of each cylinder shows whether the shape of each salt cylinder is more or less consistent with the 3D model. If the match is perfect, the color is green because it has the lowest discrepancy from the model. If the color is blue, the discrepancies are the greatest. The best printing of salt cylinders is possible with the salt-clay-straw mixture (CSS), because it has the least deformation and its shape is closest to the 3D model. The worst printed cylinder is CSS (clay, salt, starch), as it has the highest deformation. The high viscosity of the CSS printing mortar causes the printed layers in the upper area to press on the layers in the lower area and flatten. In comparison to the clay cylinder, the printed layers of the salt cylinders (CS, CSS, SSC) have a rough surface with many small salt crystals, which must be taken into account for full-size building elements. In general, more salt causes lower compressive strength and more cracks on the surface. These disadvantages can be better controlled in the future with a 1:1 scale model with more detailed research into the material properties and behaviour of the 3D printing salt mortars, stronger 3D printers and more suitable preparation, drying and curing processes.

**Table 11.** 3D scans, measurements and surfaces of four cylinders [148].

| | C | CS | CSS | SSC |
|---|---|---|---|---|
| Recipe | Clay | Clay, salt | Clay, salt, straw | Clay, salt, starch |
| Surface |  |  |  |  |
| Discrepancy to 3D model |  |  |  |  |
| Print layer size - width bottom left (mm) | 5.340 | 7.103 | 5.997 | 6.163 |
| Print layer size - width bottom right(mm) | 5.436 | 6.848 | 6.256 | 7.865 |
| Print layer size - width upper left (mm) | 5.261 | 6.684 | 6.772 | 6.963 |
| Print layer size - width upper right (mm) | 5.021 | 6.703 | 4.919 | 7.017 |

| | |
|---|---|
| 3D scan section |  |
| 3D scan section-line |  |
| 3D section width (mm) |  |

Various applications are proposed for 3D printing with salt in the future: salt as a new building material in local environments, modular and pre-fabricated salt elements, salt for healthier indoor and outdoor environments or for a green façade (Figure 177).

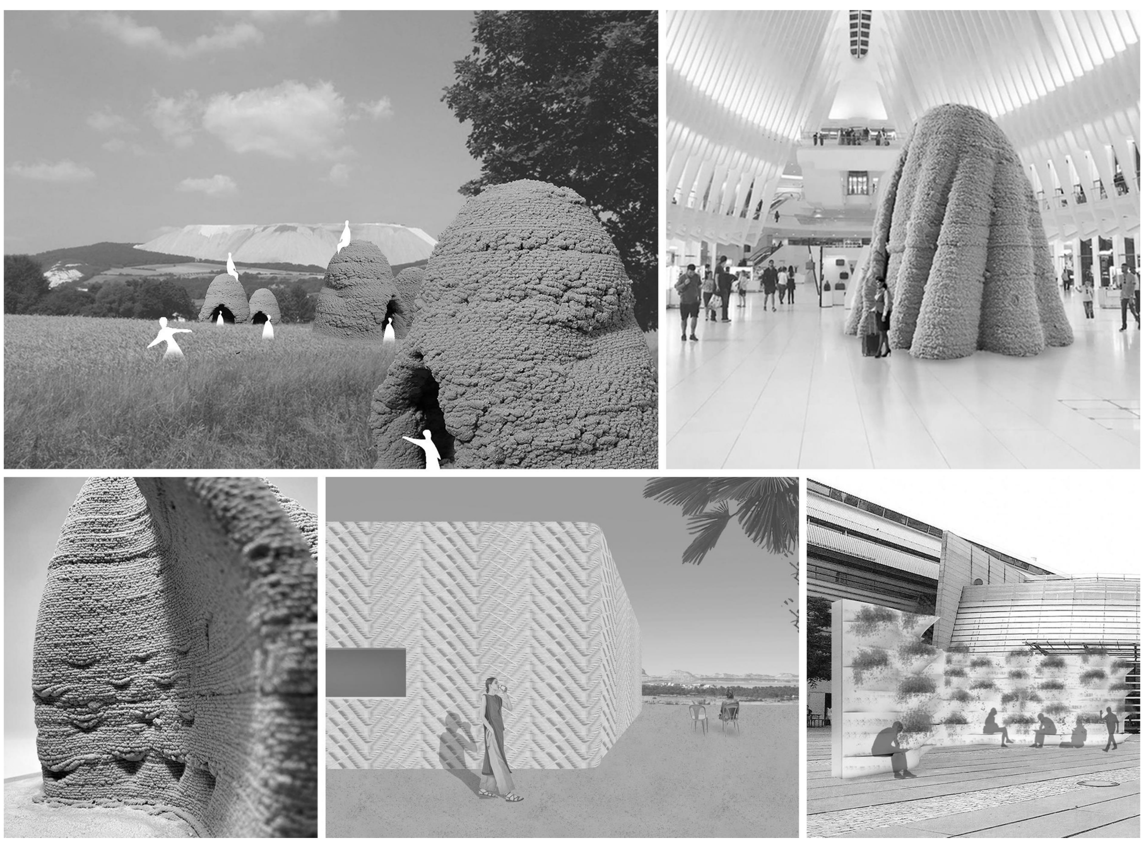


**Figure 17.** Student work: Shiyu Chen, Kai Lin, Simone Gabbana, Mehmet Yolcu, Katharina Broghammer, Philipp Neumann, Gabriele Mikalauskaite, Pinar Sel, Malaz Attar, TUM winter semester 2020 [148].

### 2.3.4 Summary of Publication 3: Reuse of salt waste in 3D printing: Case study

**Reference**

V. Pungercar, M. Hutz, F. Musso, "Reuse of salt waste in 3D printing: Case study," Proceedings of the 4th International Conference PRE|FREE - UP|DOWN - RE|CYCLE. Traditional solution and innovative technologies," pp. 236–247, 2021, ISBN: 979-12-5953-005-9.

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**Summary**

This publication presents the third step of dissertation and the first step of the research on the topic with 3D printing. The main motivation for this paper entitled *Reuse of salt waste in 3D printing: Case study* is to investigate the use of salt as an alternative material in additive manufacturing to improve the resource efficiency of the building materials (gypsum, cement, starch, clay) and speed up the construction process. For this purpose, the first case study of a small-scale 3D printing with paste extrusion is conducted.

The case study analyzes in three stages the potential of salt in 3D printing by a clay 3D printer Potter Bot Micro 10 at the Chair for Design, Construction and Materials (EBB) at the Technical University of Munich. In the first step, the recipes of salt and potential binders (clay, gypsum, cement and starch) were developed by continuous improving and modifying. In the phase, two all recipes from all material groups (SS - salt and starch, SC - salt and clay, CS - salt and concrete and SG - salt and gypsum) are experimentally printed by hand injection. The main aim was to print a cylinder of up to three layers and evaluate it with printability criteria (printed shape consistency, pumpability, proper binding time, acceptance for building up another layer and smoothness of the surface). In the final phase, the most promising salt printing mortar was selected for 3D printing of more complex designs.

The results show that SC (salt and clay) is the most promising printing mortar with up to 60% of salt and 40% clay. CS (salt and cement) printing mortar is not sufficiently plastic and took too long to dry, SS (salt and starch) printing mortar has excessive viscosity and is too fluid, while SG (salt and gypsum) printing mortar binds and dries too fast. For future research, studies with salt printing are recommended to use different additives (superplasticizer, restrainer or viscosity modifier) and different 3D printers. The results from the case study show the potentials for salt in 3D printing, which is thus recommended for futher research.

**Declaration of own contribution**

(VP: Vesna Pungercar; MH: Martino Hutz, FM: Florian Musso)

Conceptualization, Methodology, Formal Analysis, Investigation, Paper Layout, Resources, Writing (Original) was performed by VP (70.0%). Visualization, Formal Analysis, Investigation, Resources, Writing (Original) was performed by Martino Hutz (20.0%), Review and Conceptualisation was performed by FM (10%)

The overall own contribution of Vesna Pungercar for Paper 3 (Reuse of salt waste in 3D printing: Case study) is estimated at **70 %.**

### 2.3.5 Summary of Publication 4: 3D print with salt

**Reference**

V. Pungercar, M. Hutz, F. Musso, "3D print with salt" in 3D Printing for Construction with Alternative Materials, Digital Innovations in Architecture, Engineering and Construction, edited by B. Rangel er at., Springer, pp. 91-125, 2023..https://doi.org/10.1007/978-3-031-09319-7_5.

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This peer-reviewed paper will be published in a book 3D Printing for Construction with Alternative Materials, Digital Innovations in Architecture, Engineering and Construction, edited by B. Rangel er at., Springer in September 2022. The permission to integrate and use the paper as a part of publication-based doctorate of Vesna Pungercar was granded by the publisher. The paper is published as open access.

**Summary**

This publication represents the third step of the dissertation and an overview of the research on the topic with 3D printing. The main motivation for this work is to study the influence of additives on the clay-salt 3D printing mortar in small scale and analyse the future applications.

The study analyses the potential of salt in 3D printing in three phases. In the first phase (see paper *Reuse of salt waste in 3D printing: Case study*), the initial formulations of salt and potential binders (clay, gypsum, cement, and starch) were developed through continuous improvement and modification. In the second phase, the most promising salt mortar from the first phase (salt and clay) was modified by using different additives (starch and fine straw fibres) and evaluated by 3D scanning and visual assessment (pumpability, printed shape maintenance, proper binding time, possibility to build up another layer and surface smoothness).

The results show that salt mortars can be 3D printed on a small scale and the printing qualities of salt printing mortars can be well evaluated by 3D scan measurement methods. Subsequently, the 3D scans are measured and the 3D salt cylinders are compared with the design of the 3D model. The results show that all 3D cylinders printed with salt exhibit deformation after 3D printing, such as layer thickness deformation, reduced overall height, increased diameter at the bottom of the cylinder, and different surface roughness. The CSS (clay, salt, starch) cylinder has the highest deformation and smoothest surface due to the high viscosity of the starch . The salt-clay-straw (CSS) mixture has the lowest deformation and the highest surface roughness because the straw adds stability but also absorbs water too quickly and makes printing difficult. Based on the results, the resource efficiency of salt printing mortar is achieved with up to 70% of the amount of salt in the salt/binder ratio. In general, the water content in the printing mortar must be non-linearly increased with increasing salt content, and the drying process must be better influenced to reduce the surface roughness and cracking. 3D printing was also possible for several more complex 3D design objects (developed in the Winter 2020 and Summer 2021 master classes at the Chair of Design, Construction and Materials at the Technical University of Munich). However, in the future 3D printing should be performed on a larger-scale printer and the material properties of the 3D printing mortar should be further improved.

**Declaration of own contribution**

(VP: Vesna Pungercar; MH: Martino Hutz, FM: Florian Musso)

Conceptualization, Methodology, Formal Analysis, Investigation, Paper Layout, Resources, Writing (Original) was performed by VP (70.0%). 3D print strategy, Visualization, Formal analysis, Investigation, Resources, Writing - Original Draft (Original) was performed by Martino Hutz (20.0%),  Review and Writing: Review & Editing was performed by FM (10%)

The overall own contribution of Vesna Pungercar for Paper 4 (3D print with salt) is estimated at **70 %.**

# 3 Discussion, Conclusion and Future work

In this cumulative dissertation, the potential of salt is investigated based on three main tasks, namely identifying salt materials and their application in building construction, analyzing the hygrothermal performance of salt application in the building envelope and determining the most appropriate climate zones, and investigating the potential of 3D printing with salt to increase the salt content in building material.

## 3.1 Discussion

**Step 1: Literature review**

The literature review provides an overview of the properties of salt, salt materials, salt applications, and future opportunities. From the literature review, it is clear that there have been many salt materials with different applications in the past. The problems of salt crystallisation in masonry have been transformed into possibilities in the past with Karshif stone, salt concrete, or Roman martime concrete, where salt plays an important role in durability and strength under appropriate environmental conditions. Himalayan salt block is identified and further analysed as the most suitable material for interior application. However, in this part some limitations and potentials are identified, such as:

**- Lack of information on the parameters of the salt material.** Although various salt materials have been identified, a major shortcoming is the inadequate study of their properties or the lack of information on their material properties. Several studies have investigated the mechanical or chemical properties of salt materials, with some emphasizing the effects of salt on respiratory diseases, while a detailed description of the salt material or the salt-containing environment is lacking. These shortcomings are probably due to the fact that the application of salt materials in the building envelope has not been considered.

**- Lack of information on the application of salt materials in different climatic environments.** Salt materials have generally been studied without reference to specific climatic conditions. Material properties have been defined and studied, but not further optimized or simulated for different climates. There are also no studies on how salt materials affect indoor air temperature, humidity, and air quality. The hydrothermal performance of the same salt material under different climatic conditions has not been compared and discussed.

**- Lack of design methods for indoor salt applications.** There are different design solutions for salt materials without investigation and comparison of their hydrothermal performance. There is a lack of comparison between existing design solutions for indoor salt application and their impact on heat and moisture flow in the building envelope. Raw salt blocks of size 10x20x5cm are usually applied as claddings on interior surfaces, whereas other options for interior application of salt stucco, Karshif wall or Roman seawater concrete are not discussed.

**Step 2: Hygrothermal performance and its influence on indoor air quality and energy demand**

Relationships between indoor salt application and its impact on thermal envelope, indoor air quality, and energy demand were investigated under six different climatic conditions. To investigate the challenge of salt deliquescence, the most suitable climate condition and a possible replacement of gypsum are validated by 36 simulation models and experimental measurements. In general, the studies showed that the surface temperature and RH values of salt are only slightly lower than those of gypsum under most climatic conditions. Even under controlled indoor conditions, salt should not be used in very humid climates. However, buildings in very hot and dry environments may benefit most from salt, as the salt surface remains cooler, indoor comfort is higher due to relative humidity, and the risk of salt deliquescence is the lowest. The experimental results showed similar values when compared with the simulated results. There was a discrepancy between the simulation data and the real situation, although the hygrothermal performance of salt and gypsum shows the same trend of hygrothermal performances. The WUFI®Pro and WUFI®Plus simulations enable analyzing the heat-moisture process in the exterior wall and its impact on indoor air quality and energy demand. Without the combination of two simulation programs, this research would have shown greater uncertainties and could not be compared with experimental studies. However, there are some limitations that should be improved in the future:

**- Lack of information on salt-gypsum material.** The moisture and head-related material properties of salt-gypsum are not defined due to the limitations of the test equipment at TU Munich, Germany. Although the results show that the hydrothermal performance of salt-gypsum is in the range between gypsum and salt material, the material properties should be defined in the future.

**- Test materials and equipment.** The test materials are smaller in size due to space and financial constraints. The Tesla sensors are made of steel and are only used for 139 days due to the risk of corrosion. For a future investigation, larger test materials should be installed on the outer wall and at least one year measurement should be performed with special sensors. However, the first measurements proceeded without any obstacles and allowed first insights into the hygrothermal properties of salt.

**- No dynamic performance of the material in simulation programs.** The computational model in simulation programs is simplified. It cannot analyze and evaluate the consequences of the salt's contact with other materials and whether the material properties of the salt change due to the present and past heat and moisture processes. Therefore, practical, experimental investigations are necessary.

**Step 3: Application of salt in 3D printing**

In chapter 3, the possibility of using high amounts of salt in construction with 3D printing on a small scale is analysed. The results of the first case study show that the salt printing mortar can increase the resource efficiency of the building material and create complex but stable 3D printed objects, despite the fact that salt is a very porous material. However, there are some limitations that have to be improved in the future:

- **3D printer.** Potter Bot Micro 10 printer properties have been observed to have an impact on the development of salt printing mortar. Some printing mortars were added more starch and water to be forced through the printer nozzle. The speed of the 3D printer and the power were often too low. It was also found that the salt mixtures had to be carefully removed from the printer after each 3D print, otherwise the salt caused corrosion to a metal part of the printer. This process was very time-consuming.

**- 3D printing of salt mortar.** Printing properties have been analysed, although material property studies are still lacking. Understanding the material properties would help to improve 3D printing quality and understand the influence of salt.

**- 3D printing on a large scale.** This study has shown that salt can be used in 3D printing technology in large quantities and therefore should be studied together for larger printed objects in the future.

## 3.2 Conclusion

Salt is a potential new material that could not only save limited material resources by up to 80%, but also using salt as a new building material turns the challenges of global population growth and resource scarcity into opportunities. Building with salt waste from desalination and potash production processes would help to reduce pollution, provide more resource-efficient materials, and make indoor conditions more comfortable in very hot and dry climates. Identifying salt materials already used in the past, reducing the risk of salt liquefaction, and adapting to new building technologies are three of the key requirements for making salt more attractive and acceptable.

The step-by-step approach of this cumulative dissertation provides a literature review of salt materials, helps to understand the hygrothermal performance of salt compared to gypsum in different climates, and demonstrates one of the potential applications in construction through 3D printing. Previous research studies have usually focused only on one salt material or one property of salt material, which does not allow fully understanding the potential of salt waste in construction.

Salt in building would contribute to resource and energy efficiency. However, due to salt-related problems in masonry, salt liquefaction, and corrosion, salt is hardly accepted as a building material nowadays. Addressing and solving these problems in this work helps to increase the confidence in salt.

The step-by-step methodology offers suggestions for other research projects about:

**1. The study framework for salt materials in construction**. The identification, analysis, and application of salt as a new construction material is a challenging task that is divided into three smaller areas in this dissertation. These areas allow for individual complex studies while pursuing the same goal, namely to analyse whether salt can be used in construction at all. A step-by-step approach provides an overview of different methods: state of the art, model studies and empirical observations.

**2. The development and comparison of simulation (computational) and measurement studies for salt materials**. Numerical studies (simulation models) with WUFI®Pro and

WUFI®Plus are efficient to analyse a large number of different hygrothermal situations in a short time. Measurement studies show real observations and help to understand the salt material in a real situation. Both studies ultimately show similar results and support each other.

**3. The basis for more detailed studies on salt materials**. By defining the advantages and disadvantages of salt, further limits of the salt material were found, opening new areas for further research. The research approach requires overcoming several challenges, such as specific material properties, appropriate simulation models, and laboratory testing capabilities. All of these individual components influence the results and enable conclusive studies. It holds strong interest that other researchers are also conducting numerical and measurement studies to better understand the salt material in construction.

The condititons for the application of this step-by-step method are given for research projects:

**1. Where the new building materials are investigated.** For the new building materials, it is first important to determine from the literature if there are any existing studies on this material. A literature search should be conducted on the properties of the material and examples of its application. In the end, the literature review may provide some answers about the performance and application of the material and identify potentials for further research.

**2. Where the hygrothermal performance of materials should be analysed.** The hygrothermal performance of different materials used in the building envelope provides insight into how new materials affect the thermal envelope and indoor environment. Comparison with another commonly used material makes measurements and simulations more understandable and its substitution more comprehensive. However, the material properties of all materials should be known, otherwise simulations and measurements are difficult to perform.

**3. Where the new construction processes are implemented.** New construction processes such as 3D printing also require new methods for evaluating the material. In this study, 3D sceening was used to analyse the change of printed salt cylinders. This method allowed numerical analysis of changes such as the quality of the printed mortar, the change in shape before/after the drying process, and the surface quality. For similar research projects, a method with 3D sceening is time-saving and provides a lot of information.

The environmental benefits of implementation of salt are measured by:

**1. Changes in the consumption of natural resources**. If salt were used as a new building material or mixed with other materials up to 20%, the consumption of some natural resources could decrease. In the case of FGD gypsum in Germany, 20% salt in the salt-gypsum mixture could save 1.4 million tonnes of FGD gypsum and about $11.4 million (the United States produced 20 million tonnes of gypsum for $160 million in 2019) [149]. With the expectation that salt panels with up to 100% salt content could be developed in the future for dry indoor climates, the numbers for gypsum could be even higher.

**2. Changes in $CO_2$ emissions**. Salt is available as a by-product of desalination and the potash industry and could be used directly, without additional energy input in its production. In the case of gypsum, each tonne of gypsum replaced by salt would mean a saving of 140.7 kg $CO_2$ [150], and in the case of cement this would mean a saving of 700 to 900 kg $CO_2$ [151]. In the case of FGD gypsum in Germany, a salt content of 20% in the salt-gypsum mixture could save about 1 million tonnes of $CO_2$ per year (for 1.4 million tonnes of FGD gypsum).

**3. Changes in environmental pollution**. With approximately 8.88 million m3/day (6.8 billion tonnes/year), salt waste is nowadays disposed into nature in most cases. With the increasing demand for fresh water and fertile soil, salt waste and its environmental consequences are increasing day by day. Every tonne of salt used in the circular economy could help to reduce pollution in marine and coastal flora and fauna. Salt should not be used only once, but rather reused and recycled as often as possible.

## 3.3 Future Work

Considering that this is the first time that the salt materials have been identified from the literature and the hygrothermal performance of salt application for indoor use has been studied, there remain many issues that should be studied, applied in the future:

**- Salt mixtures.** New additives, binders, or surface treatments should be investigated to improve the properties of salt materials, e.g. to control salt deliquescence even at higher humidity. Salt mixtures should be analytically tested for their chemical properties and compared with hygrothermal and mechanical properties to gain a better understanding of their behaviour.

**- Salt and health.** The number of people with chronic respiratory diseases is increasing every year. Non-medicinal treatments include speleotherapy, halotherapy and climatotherapy, which have in common that they inhale the air saturated with salt particles (aerosols) in salt caves, salt rooms or at the sea. It is necessary to investigate whether there is an exchange between saline building material and air and under what conditions (dry air, humidified air, efflorescence) the air is enriched with salt.

**- Salt and hygrothermal performance.** It would be necessary to study and compare salt-binder materials for their hygroscopic properties, as binders, support structures, and additives could be used to improve heat and moisture transfer. These materials should then be studied under real conditions and in-situ measurements could be taken under different climatic conditions.

**- Salt and 3D printing.** In the future, 1:1 scale printing should be performed using the salt printing mortar. In addition, the requirements of paste extrusion with those of the powder process should be investigated and recorded.

The limitations and possible contexts of salt in construction have already been discussed above. However, it may be appropriate to address possible projects in construction that could be investigated/studied:

- **Wall and cladding salt panels in climates with low humidity.** Salt should be mixed with other materials and processed in various ways. Measurements should be made to analyse the effect of salt on load-bearing capacity (tension/compression), heat storage, and abrasion resistance. Mixtures with suitable properties should be used in formwork and with supporting structures. Cladding salt elements with different reliefs and degrees of crystallization of the surface should be used in realistic test setups and measurements to show whether and how the exchange between particle-based building materials and air takes place. The developed panels should have the highest possible salt content and an attractive appearance with enlarged surface structure. It is estimated that 30-50% of commonly-used materials (cement, gypsum, clay) could be replaced by salt.

- **A salt filling material for interior walls in dry/hot climates.** Salt is non-combustible and has good acoustic properties (higher bulk density than wood). It can be used as a filling material for interior walls in dry/hot climates. Measurements such as salt grain size, construction process, and appropriate wall construction should be made to determine the most appropriate non-load-bearing wall construction. Interior walls should have varying sizes and degrees of light transmission. It is estimated that 60-80% of the interior wall material could be replaced with salt.

- **Modular pre-fabricated elements.** Saline building elements can be industrially manufactured and placed in locations with appropriate weather conditions. If the humidity is below 75% RH, pre-fabricated modular elements can stick together due to the formation of salt crystals during drying. This means that – for example – no special mortar is needed for the joints between modular pre-fabricated elements. In this project, the different salt mixtures should be analysed and identified. Different environmental conditions (temperature and RH humidity) and shapes of the elements should be used to define the most suitable conditions for drying and bonding. It is estimated that 30-50% of the commonly-used materials (cement, gypsum, clay) could be replaced by salt.

- **Temporary building of salt.** Salt raw materials or brine are suitable for temporary buildings such as pavilions, trade fair construction, shading systems. Temporary building structures in very hot and dry climatic conditions could be achieved with the technique of growing salt crystals, erected after the evaporation of sea water and later demolished with water. It is estimated that 50% of the material could be replaced by salt.

**- Load-bearing walls.** Salt materials can be adapted to printing processes. 3D printing does not always use steel for reinforcement, and strength can be improved by admixtures. Salt should be mixed with other materials and other reinforcement. Measurements should be made to analyse the effect of salt on load-bearing capacity (tension/compression). Mixtures with suitable properties should be used in formwork and could be protected with coatings in 3D-printed walls or placed inside structures. It is estimated that 10-30% of the material (concrete for example) could be replaced by salt.

**- Salt wall paint**. Salt is antibacterial and could be mixed with common wall paints to reduce the risk of mould growth. In this research project, different wall paints and amounts of salt should be mixed and tested. Salt wall paint mixtures with suitable properties should be used and tested at different relative humidity, temperatures, and wall materials. It is expected that mould growth on the wall with salt wall paint would be lower than with common wall paint.

- **Salt for a circular economy.** This research project should investigate how salt can be reused to reduce its environmental impact. Various durability studies and uses after the original intended use has expired should be investigated.

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# 4 Appendix A: Full texts of the publications

## A-1: Paper: Salt as a Building Material: Current Status and Future Opportunities

V. Pungercar, F. Musso, “Salt as a building material: Current status and future opportunities,” PLAN Journal : research in architecture and urbanism, vol. 6, pp. 393-413, 2021, doi:https://www.doi.org/10.15274/tpj.2021.06.02.4.

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# Salt as a Building Material: Current Status and Future Opportunities

Vesna Pungercar, Florian Musso

ABSTRACT - *Identifying materials that can substitute rare natural resources is one of the key challenges for improving resource efficiency in the building sector. With a growing world population and rising living standards, the amount of salt (sodium chloride) produced as waste through seawater desalination and potash mining processes is increasing. Unfortunately, most of it is disposed of into nature where it causes environmental pollution. On the other hand, salt is affordable and can be used therapeutically in various respiratory treatments and to store humidity and heat. It was, therefore, necessary to determine salt materials already in use in building construction. The aim of this research was to identify those that have been used in history and analyzed in scientific studies, to investigate their physical and mechanical properties, and to identify the most promising applications in the construction field. This was accomplished via literature review, classifying the salt materials into three groups (raw salt, composite salt, and processed salt). It was found that salt has been used as a building material for centuries and has potential for future applications.*

**Keywords:** building material, history, material properties, salt materials, salt waste

Salts [1,2,3,4,5] are defined in chemistry as compounds of cations (positively charged ions) and anions (negatively charged ions). Sodium chloride (NaCl), or common salt, is the most known of all salts and consists of Na (Sodium) and Cl (Chloride) ions. It can be found in natural underground deposits as salt rocks (halite) or in seawater or brine as dissolved constituents. Salt rocks were formed through many geologic periods by tectonic movement and pressure on salt evaporation ponds (crystallization of salt in saline water by solar evaporation).[6,7] Dissolved salt particles are gained back from seawater or brine through natural solar evaporation (salt ponds) and mechanical evaporation.[8,9]

However, other sources of salt are emerging as a result of the growing world population:[10] salt from desalination plants and from potash mining. Fresh water is produced from seawater in desalination plants, with a discharge into the sea of around 142 million $m^3$ [5,014,682,674 ft.3] of salt brine waste per day.[11] A similar situation [12] is observed in intensive agriculture, where nutrients are added to the soil to speed up plant growth. One of these fertilizers is potash and for its production a high amount of salt waste is created (between 51,742.98 m3 [1,827,286 ft.3]/day and 436,956.29 $m^3$ [15,430,965 ft.3]/day).[13] The negative environmental impacts of salt waste discharge such as change of salinity, increase in temperature, and loss of biodiversity in both maritime and freshwater environments, have been acknowledged in many scientific studies.[14,15,16] With this in mind, using salt as a building material may increase resource efficiency while reducing the salt contamination of flora and fauna.

On the other hand, salt is an affordable natural product [17,18] and can store humidity [19,20,21] and heat.[22,23,24,25,26] In terms of material humidity, Feldman [27] described NaCl as a hygroscopic material with a critical point of solubility of 75.3% relative room humidity at 20 $^0$C room temperature. The specific heat capacity of sodium chloride in its pure state varies from 0.853 J/(gK) 28 to 0.859 J/(gK).[29,30] Salt can deactivate the growth of microorganisms 31 and is used not only therapeutically in various respiratory treatments [32,33,34,35,36] but also for skin diseases such as atopic dermatitis [37] or human lung cancer.[38]

For 7,000 years salt was mostly used in cooking and the conservation of food and later for trading, while currently it can be found in 14,000 different applications in the chemical and food industry.[39] However, salt in the field of building construction is associated with damage in masonry. With the increasing water content in brick masonry, salt dissolves and moves together with water through the capillary pores. In drier and hotter climate conditions, the water evaporates and salt crystalizes. Salt crystallization in the capillary pores produces an interior pressure and can cause deterioration and efflorescence of the brick.[40]

Due to its salt-related problems in masonry, its high value in history, legally restricted availability, high porosity, and dissolution in water, salt is still not fully accepted as a building material. However, examples exist of salt building materials used in various applications: protecting the disposal of radioactive waste,[41,42] defending Roman harbors,[43,44,45] for building houses in deserts,[46,47,48,49,50] and optimizing indoor air quality.[51,52,53,54,55,56,57,58,59,60,61]
Salt building materials have further potential advantages in increasing

resource efficiency; they have attractive hygrothermal properties, are not inflammable, and are antibacterial. However, no general analysis of salt's application as a building material and its properties exists. Thus our study investigates the potential and limitations of using salt in building construction.

The state of the art is organized in a two-group framework that shows salt at two different levels. At the micro level, the basic information about salt (classification, crystallization, and physical and chemical material properties) is provided without specific application purposes. At the meso level, the research is about raw salt, composite salt, and processed salt, shown at the level of a loose product. This review study revealed that there was almost no research on the topic of salt building materials and thus opens up research areas that merit investigation.

## PROPERTIES OF SALT (NaCl)

"Sodium is the sixth most abundant element in the Earth's crust" [62] and its compound sodium chloride the most known in human society. Most properties of salt depend on the production process and geological history and the purity and content of other minerals, as well as interactions between the particles and pore spaces. Table salt or sodium chloride, NaCl, is a compound of two ions: Na (sodium) and Cl (chloride). A bond between these two ions is called an ionic bond, where electrons from one atom are transferred to another.[63,64] All ions are connected in a cubic lattice, which can have any number of ions depending on the size of the crystal.[65] Salt crystals (Fig. 1) are transparent and colorless, and the crystalline powder is white.

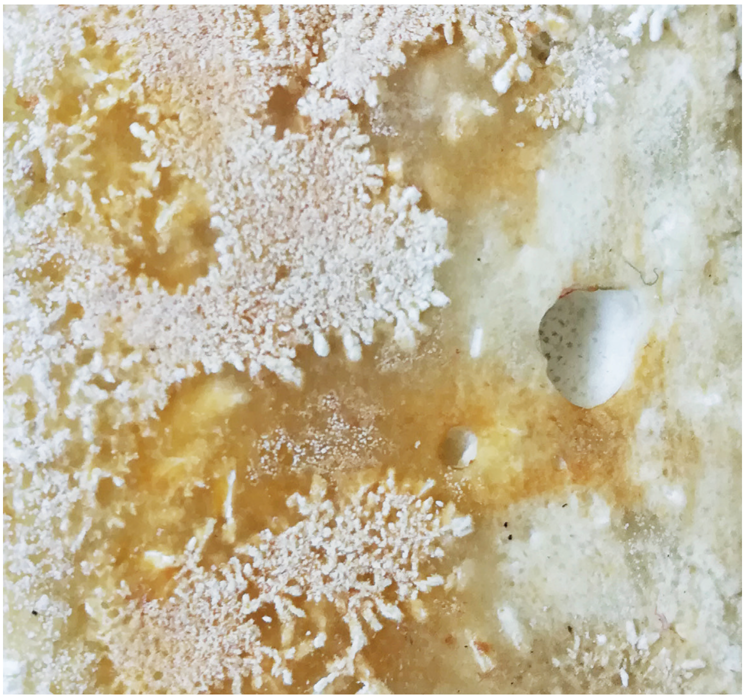


Figure 1. Salt crystals.

Different studies show that the permeability and porosity of salt are low [66] due to a lack of open spaces within the material. Salt is applied for sensitive heat storage in solar power plants [67] due to its high melting point.[68,69] If small impurities such as anhydrite, gypsum, dolomite, calcite, pyrite, quartz, or iron oxides are present in salt, the bulk density value (from 2.17 g/cm³ to 2.25 g/cm³ at 20 $^0$C) and specific heat capacity (from 0.853 J/(gK) to 1.224 J/(gK)) are increased.[70,71,72,73] Salt is soluble in water, methanol, or formic acid, but not in ethanol or glycerol.[74] In terms of material humidity, at more than 75.3% relative humidity,[75] the pores in salt are filled with water, the crystals start to dissolve and brine is formed. If relative humidity decreases, the brine evaporates and re-crystallization takes place. This repeating process within salt generates strong connections between crystals and throughout history, therefore, has been used to create strong materials. The detailed chemical and physical properties of salt are listed in Table 1.

| Property | Value / Form | Literature |
|---|---|---|
| **Salt cristallisation** | cubic shape | (Desarnaud et al. 2018; Fontana, Pettit, and Cristoforetti 2015; Graef and McHenry 2012; J. Zhang et al. 2011) |
| | pyramid shapes, hollow cubes or skeletal hopper | (Desarnaud et al. 2018) |
| **Bulk density** | 2.165 g/cm³ at 25 | (National Center for Biotechnology Information 2020) |
| | 2.17 g/cm³ at 20 ºC | (Merck 2018) |
| **Porosity** | lower than 3.8% | (Las Cuevas 1997) |
| | less than 10−17% | (Berest, Brouard, and Durup 2001; Cosenza et al. 1999) |
| **Melting point** | 801 °C | (Ferguson 1922; National Center for Biotechnology Information 2020) |
| **Specific Heat Capacity** | 0.853 J/(gK) | (Feldman 2003) |
| | 0.859 J/(gK) | (Las Cuevas 1997; Håkansson and Andersson 1986) |
| | 1.224 J/(gK) | (Gevantman 1981) |
| **Thermal Conductivity** | 6 to 6.5 W/mK at room temperature | (Sayem Zafar 2015; Ohlsen 1956; Feldman 2003; Lorenz et al. 1981; Durham and Abey 1981) |
| **Solubility** | 75.3% relative room humidity at 20 ºC room temperature | (Feldman 2003) |
| **Health** | Speleotherapy (climate of salt caves) | (National Center for Biotechnology Information 2020; Abdullaev, Gadzhiev, and Eiubova 1993; Horowitz 2010; Horvath 1986; Lăzărescu et al. 2014; Puryshev 1994; Skulimowski 1965; Beamon et al. 2001) |
| | Halotherapy (re-makes of climate of salt cave) | (Chervinskaya and Zilber 1995; Hedman et al. 2006; Horowitz 2010; Khan and O'Driscoll 2004; Rashleigh, Smith, and Roberts 2014; Zając et al. 2014) |
| | Climotherapy (Marine climate) | (Papathanasopoulou et al. 2016; Ferron, Kreyling, and Haider 1988; Kite-Powell et al. 2008) |
| | Saline device (Sprays) | (Asselman et al. 2019; Horowitz 2010; Jeong, Heo, and Lee 2019; M. Terman and J. S. Terman 1995; van Acker et al. 2020; Elkins et al. 2006) |

Table 1. Properties of salt (NaCl).

## TYPES OF SALT MATERIALS

Salt materials in this paper are divided into three groups (Fig. 1): raw salt materials (RS), composite salt materials (CS), and processed salt materials (PS). Raw salt materials consist of solid salt blocks with the highest NaCl content (Table 2) extracted directly from nearby salt lakes.[76,77,78] Romans mixed seawater, volcanic ash, and lime to create extremely durable concrete despite constant exposure and contact with seawater.[79] This and other materials mixed with a salt content of up to 95% (Table 2) is classified as CS material. Processed salt materials are materials in which salt is compressed [80,81,82] or which use natural evaporation of salt solution for growing NaCl crystals.[83,84,85,86,87]

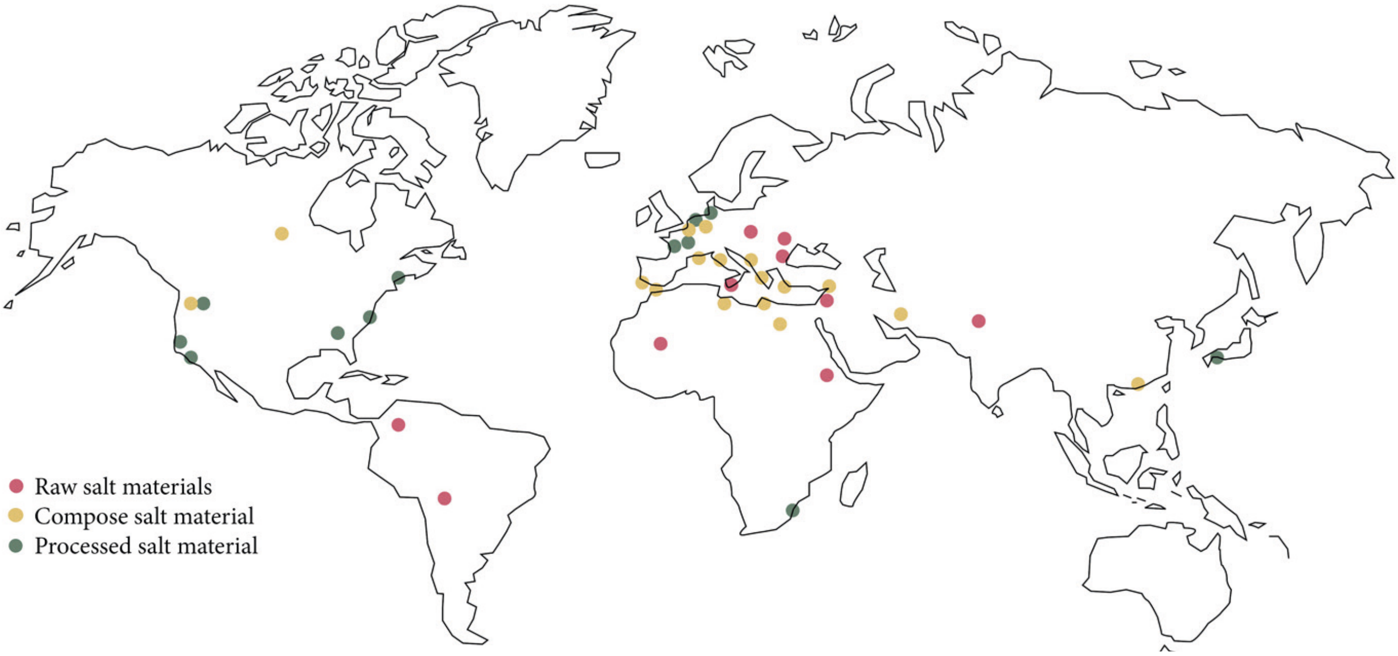



Figure 2. Types of salt materials found in the literature.

| | Name or Location | NaCl content (%) | Additives content (%) | Literature |
|---|---|---|---|---|
| **Raw salt material** | Salar de Uyuni, Bolivia | 95 | 5 | (Risacher and Fritz 1991) |
| | Himalayan, pink salt | 84.15-98.30 | 1.70-15.85 | (Sharif, M. Hussain, and M. T. Hussain 2007) |
| | Rock salt | 80.11-98.73<br>76.1-99.80<br>71.27-99.09 | 19.89-1.27<br>0.2-23.9<br>0.91-29.73 | (Las Cuevas 1997)<br>(Durham and Abey 1981)<br>(Las Cuevas 1997) |
| | Salt block of the City of Getta | N.A. | N.A. | (COUCH 1847-48) |
| | Salt block of the City of Teghasa, Mali | N.A. | N.A. | (Gibb and Beckingham 2017) |
| | Salt block of the abandoned village of Dallol, Ethiopia | N.A. | N.A. | (Cavalazzi et al. 2019) |
| **Compose salt material** | Karshif salt block - Siwa Oasis, Egypt<br>Old masonry karshif<br>New masonry karshif | max. 95<br>86<br>75 | 5<br>14<br>25 | (Petruccioli and Montalbano 2011)<br>(Rovero et al. 2009)<br>(Rovero et al. 2009) |
| | Roman sea-water concrete, Roman time | 0.2-0.7 | 99.3-99.8 | (John Peter Oleson 2014) |
| | Salt and starch | 80<br>53.3 | 20<br>46.6 | (Ganter 2011; Geboers 2015b; Rael and San Fratello 2018)<br>(Marutani and Kamitani 2004) |
| | Salt and alginate | ca.5 | 95 | (Wei, Luo, and Huang 2019) |
| | Salt concrete | 53.8 | 46.2 | (DBE 2004) |
| | Salt stucco | N.A. | N.A. | (Iran Treveller 2015) |
| **Processed salt material** | Compressed Salt material | 96<br>95 | 4<br>5 | (Viard 1979; Orton 2002)<br>(Mandler et al. 2018) |
| | Crystalized Salt | 3.5 | 93 | (FAULDERS STUDIO 2009; Manor et al. 2019; Meinhold, December 07, 2013; Sibbel 2017) |

Table 2. NaCl content in different salt materials.

*Raw Salt Materials*

Knowledge about RS materials is based on very limited historical data. Most historical examples have in common severe climate (very hot and dry), specific location (near salty lakes and salt mines), and unavailability of other local construction materials. Pliny the Elder wrote in the 1st century A.D. about the city called Getta, apparently located in the region of Pella and Damascus as being "fortified with towers made of square masses of Salt." [88] In the 14th century the Moroccan traveler Ibn Battuta describes the city Taghaza in Mali as "a village with no attractions. A strange thing about it is that its houses and mosques are built of blocks of salt and roofed with camel skins. There are no trees, only sand in which there is a salt mine." [89]

Another abandoned town in the Danakil Depression in Ethiopia is Dallol which shows destroyed walls built in the past from salt blocks.[90] The single-story walls of the buildings were built of irregular medium-format salt blocks cut from the surrounding area and bonded with a mortar. Salar de Uyuni in Bolivia is the largest salt flat on Earth located above sea level and its salt crust consists of 95% halite and 5% fine-grained gypsum.[91] This monolith-like salt stone is cut from the ground, shaped, and used as a construction material for buildings. One of these buildings, which is built out of some one million salt blocks, is the hotel Palacio de Sal.[92] Other RS materials are rock salts from salt mines [93,94,95,96,97,98,99] with bulk density from 1,920 kg/m$^3$ to 2,160 kg/m$^3$, low porosity (0.6–7.2%), specific heat capacity around 865 J/kgK, thermal conductivity from 2.65 to 6.65 W/(mK), widely varied hygroscopic properties due to different additive contents, and compressive strength ranging from 3.3 to 20.7 MPa (Table 3). Pink salt blocks are the most conventional rock salts [100] and are used in the interiors of spas, restaurants, and residences.

*Composite Salt Materials*

Both in history and today, CS materials in history have combined different local materials according to resource availability and to improve material properties. The first combinations occurred between salt and local materials such as clay or volcanic ash. Karshee or Karshif is a salt block (NaCl) enriched with clay and sand, which is first dried under direct sun exposure and then used as a "brick" in the Kershee masonry building technique found in Siwa Oasis in Egypt.[101,102] Dried salt bricks from nearby salt lakes are bound with soil and salt-rich mud mortar called *tilaght*. In comparison to salt rocks, a Karshif stone has more impurities and shows lower values in terms of density, porosity, hygrothermal properties, and compressive strength (Table 3).

Under specific Siwa Oasis climate conditions, the movement of water between the salt blocks and the mud causes the formation of new salt crystals resulting in "a high mechanical resistance of the masonry." [103]

Analysis of these “stones” shows that the oldest blocks are composed of 95% salt.[104] Compared with sandstone and limestone, Karshif stone shows the highest thermal conductivity with 1.62 W/mK and the lowest specific heat capacity with 0.71 kJ/kgK.[105] However, if the environmental relative humidity exceeds 76%, the sodium chloride in the Karshif stones starts to dissolve. Conversely, at a relative humidity of less than 76% the sodium chloride crystals start to grow.[106,107,108] It has been observed that under these repeated cycles of drying and wetting salt blocks and mortar transform to “a sort of monolith.” [109]

Concrete is a composite material that has been used in many ancient structures. The Romans discovered how to make it very durable and waterproof for use in seawater.[110] They mixed volcanic ash, lime, and seawater [111] and built robust protection walls for their harbors in the Mediterranean Sea. The chemical and mechanical properties of Roman concrete were determined with core segments drilled from ancient structures.[112,113,114] More information about the influence of seawater or salt on modern concrete can be found in several studies in the literature.

In comparison to concrete mixed with fresh water, that mixed with seawater (Table 3) shows an increase in density,[115,116] setting times,[117,118,119] and compressive strength after seven days.[120,121,122,123,124] On the other hand, the porosity [125,126] and water absorption decreased.[127,128] After twenty-eight days, the long-term compressive strength [129,130,131] between both concrete mixtures is almost the same. Concrete mixed with a high amount of salt is called salt concrete and is used for the protection of natural radiation and to prevent leakage of radioactive waste in salt caves.[132,133]

Salt concrete and salt caves create strong bonds with each other,[134,135,136,137,138] producing a more secure protection for radioactive waste. A salt concrete composition for the safe disposal of radioactive waste in Morsleben, Germany was made of cement, fly ash, water, and salt (53.8 mass-%).[139] In comparison to commonly used concrete, test results of salt concrete showed lower Young’s modulus values, similarity in strength, higher porosity, and lower permeability. The values of specific heat capacity ($C$= 0.93 kJ/(kgK)) and heat conductivity ($\lambda$=1.14 W/(mK) of salt concrete are lower than those of concrete. More or less identical material properties were found by Czaikowski et al.[140]

In the last ten years, salt and starch mixtures have been used in the building area for research purposes in the field of additive manufacturing.[141,142,143] Dr. Mark Ganter and his team started experimenting in 3D printing using a salt-starch compound.[144] His recipe of salt (eight parts by weight) and maltodextrin (one part by weight) was later used by researchers from the University of California and by Geboers/TU Delft to create different 3D-printed salt objects [145] and to determine density, tensile, and compressive strength.[146] A University of California team mixed salt and maltodextrin, bound it with rice wine and strengthened it with wax.[147,148] Salt-starch [149] showed, in comparison to modern concrete, only one part to thirteen of the compressive strength and two-thirds of the density (Table 3).

Japanese researchers [150] also mixed salt with starch but then added wheat flour and dextrin. Their material was 3D-printed as a scaffold and used as a mold for other materials. When the conglomerate was soaked in water, the salt-starch dissolved and the complex structure remained. The Iranian company Emtiaz Architecture & Design Group [151] mixed salt and natural gum to create a stucco-like salt material for the walls, structural sculptures, and ceilings of a fast-food restaurant near Shiraz in Iran to imitate a salt cave environment. Material ratios have not been published in the accessible literature.

*Processed Salt Materials*

Processed salt materials are produced by processing technologies such as pressing or melting and by the natural processes of salt crystallization. Compressed salt materials were first manufactured as salt lick blocks [152] for livestock nutrition.[153] However, the corresponding literature states that using salt lick blocks for building construction [154] cannot be sustained if the salt is not mixed with additives [155] or coated with epoxies.[156] Schelven experimented with salt extracted from salt mining and salt desalination processes. In order to provide a temporary waterproof coating, salt blocks were dipped into paraffin at lower and higher temperatures as well as into epoxy for two hours at 150–350 °C [302–662 °F] to develop a permanent waterproof coating. The resistance to water and humidity of salt blocks was examined by Mandler and his group in 2018,[157] where a small amount (0.1–15 wt%) of an additive was added to sodium chloride. Depending on the material properties, compressed salt blocks did not completely dissolve when exposed to water. Moreover, the samples preserved the main core and exhibited compressive strength in the range of 40–70MPa (Table 3).

It was also found that when subjected to humidity, salt objects with additives did not start to dissolve below 74% relative humidity at 40 °C [104 °F]. Furthermore, at 74% relative humidity the blocks held their shape for eight hours, some for even longer at higher relative humidity. Pressed salt interior design elements in the form of a marble-like set of tables and chairs have been created by the artist Roxane Lahidji [158] who pressed a mixture of salt, tree resin, and coal powder. An experimental study in 2013 [159] went even further and observed how the bonds between sodium chloride with Na-ions or Cl-ions changed under extreme application of pressure and temperature conditions similar to those in the universe. It was noticed that new bonds similar to metallic bonds appeared.

Salt crystallization processes such as salt crystal growth by seawater evaporation or salt crystal growth in very salty water has mostly been

| Salt material | Bulk Density (kg/m³) | Porosity (%) | Specific Heat Capacity (J/(K kg)) | Thermal Conductivity (W/(m·K)) | Water Vapor Diffusion Resistance Factor (dry 23°C, 50% RH) | Water vapour resistance factor "Wet" cup (μ-value) | Moisture Buffering Value (M.-%) | Compressive strength (MPa) | Kinematics ductility | Elastic modul (psi) |
|---|---|---|---|---|---|---|---|---|---|---|
| Pink Salt Rock (Fraunhofer IBP 2020b, 2020a) | 2162 | 3.50 | 865 | 2.650 | 1113-14559 | 10.3-1172 | 23.6* | - | - | - |
| Salt rock (Las Cuevas 1997) | 2130-2220 | 0.97-3.09 | - | - | - | - | - | - | - | - |
| Salt rock (Bauer, Song, and Sanborn 2019) | 2090-2160 | - | - | - | - | - | - | 17.1-22.3 | - | - |
| Salt rock (Van Sambeek L, Fossum A, Callahan G, Ratigan J. 1993) | - | - | - | - | - | - | - | 12-32 | - | - |
| Salt rock (Durham and Abey 1981) | 2160 | 1.00 | - | 6.30 ± 0.60 | - | - | - | - | - | - |
| Salt rock (Gevantman 1981) | 1920-2970 | 0.62-7.17 | 1.224 | 6.650 | - | 0.00-3.24 | - | 3.3-20.7 | - | - |
| Karshif (Makhlouf et al. 2019) | 1970 | 21.29 | 710 | 1.62 | 15.77 | 3.11 | 12.3 | - | - | - |
| Old masonry karshif (Rovero et al. 2009) | 1550 ± 20 | 26±3 | - | - | - | - | - | 9.74 | 2.10 | 774.63 |
| New masonry karshif (Rovero et al. 2009) | 1540 ± 20 | 33±1 | - | - | - | - | - | 2.66 | 3.67 | 347.17 |
| Roman sea-water concrete (E. Gotti et al. 2008) | 1390-1415 | - | - | - | - | - | - | 3.5-5.6 | - | 3730-5160 |
| Roman sea-water concrete (John Peter Oleson et al. 2004) | 1542-2163 | - | - | - | - | - | - | 4.9-9.4 | - | 4850-18800 |
| Salt and starch (Geboers 2015a) | 1234 | - | - | - | - | - | - | 5.28 | - | - |
| Salt and concrete (DBE 2004) | 1965 | 18.00 | 930 | 1.14 | - | - | - | 24.1 | 2.50 | 25680 |
| Salt and concrete (Griffin and Henry 1962) | - | - | - | - | - | 5.30-29.27 | - | 35.5-61.70* | - | - |
| Concrete with seawater (Sikora et al. 2020) | - | - | - | - | - | - | - | 56 - 83.5 | - | - |
| Concrete with seawater(Kaushik and Islam 1995) | - | - | - | - | - | - | - | 39.5-49.5 | - | - |
| Salt concrete(Etxeberria, Fernandez, and Limeira 2016) | 2080-2340 | - | - | - | - | - | - | 29.9-51.3 | - | - |
| Salt concrete(Erniati et al. 2015) | - | 10.50 | - | - | - | - | - | - | - | - |
| Compressed Salt material (Mandler et al. 2018) | 1700-2300 | - | - | - | - | - | - | 40-86 | - | - |

*reviewed properties were tested at different conditions as in norms.

Table 3. Review of salt material properties.

used by artists and architects.[160,161,162,163,164] The artist Sigalit Landau [165] sunk everyday objects into the salty Dead Sea. Karljin Sibbel [166] created small stand alone salt structures such as seats or vases by controlling the crystallization process. In 2009 Wen Ying Teh [167] suggested an observation building for flamingos made of aluminum frames and nylon ropes that absorb salt water from the lake, forming a translucent crust through the evaporation of water. A similar concept was also developed by the architectural office Faulders Studio [168] and the French architectural office Sitbon Architecture.[169] A thin plant-based wall panel with a surface of salt crystals was designed by Jessica Owusu Boakye to provide good indoor climate conditions in spaces of relaxation, rest, and exercise.[170]

*Salt in Building Applications*

For the earlier uses of salt as a building material, climate conditions (very dry and hot), material availability, and local construction techniques were important. Initially, salt blocks were used mainly as masonry (connected with mortar) to build exterior or interior walls. However, with the development of other manufacturing techniques and material mixtures, new salt applications emerged: salt for cladding, plastering, protection of walls, and temporary constructions. In the near future, we expect salt will be used in additive manufacturing (3D printing) to save time and money. In Table 4 we consider known applications of salt materials with their target material properties and evaluate their limitations and advantages.

Many past applications are no longer applicable in contemporary practice as there may be a lack of craft knowledge, they are too time consuming, or other necessary materials are no longer available. The design criteria for the current/future use of salt in building construction should therefore be carefully considered. First, salt as well as any additional materials should be locally available. Second, depending on whether the salt construction is used outdoors or indoors, the air temperature should be at the desired level and the air humidity lower than 70%. Third, the material's mechanical properties must be sufficient to obtain structural firmness. Finally, a high amount of salt is preferred.

Our current research shows that the most economical way of using salt in construction is to mix it with other building materials. It can be mixed in, added to molds, or dried and fixed on a wall surface. Fig. 3 shows how to apply salt plates on a supporting construction. Another method would be to print salt binder mixes with a 3D printer to create stable exterior wall constructions and 3D elements (Fig. 4). Apart from the above-mentioned design features, these also have the advantages of durability, design freedom, economy, and construction speed.

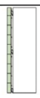
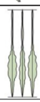
| Structure | Material with % weight of salt | Image | Advantages | (Possible) Limitations |
|---|---|---|---|---|
| **Interior wall** | Karshif salt block, ≥ 75% |  | - Simple technology<br>- Initial cost low<br>- Rough wall surface<br>- High fire protection | - A lot of handwork (local technique) needed<br>- Time consuming - salt stones have different shapes<br>- Available only in the Siwa Oasis<br>- Poor mechanical properties<br>- Soluble in water |
| | Salt block from salt lakes, ≥ 95% |  | - High resource efficiency<br>- Smooth white surface<br>- Low pollutant emissions<br>- Integration of electric cables possible | - Application possible only in very dry, hot climate conditions<br>- Much handwork<br>- Possible to connect rectangular blocks with diferent mortar mixes |
| **Exterior wall** | Salt block from salt lakes, ≥ 95% |  | - Humidity and temperature storage possible<br>- Natural white material<br>- Antibacterial | - Much handwork<br>- Walls have to be protected from water<br>- Walls are thicker, less sunlight can penetrate inside |
| | Salt concrete, ≥ 53% |  | - Easy to mix and to build with (no skilled craftswork)<br>- Good mechanical properties<br>- Higher resistency to water than other salt materials<br>- Salt waste can be used | - Built only in salt caves<br>- No other application known |
| **Wall covering (plaster, tiles)** | Salt block from mines, ≥ 84% |  | - Can be fixed with steel profiles, glued or hung on a mesh<br>- Factory prefabrication possible<br>- Damaged blocks can be replaced | - Very heavy elements<br>- Import from Pakistan<br>- Expensive<br>- No salt waste used<br>- Only for indoor applications |
| | Salt stucco, % not known |  | - For interior and exterior applications<br>- Thin and thicker layers possible | - Much handwork<br>- Combination with natural gum (rare and expensive) |
| **Seawater structures** | Roman sea-water concrete, ≥ 0.2 |  | - Possible to build in seawater<br>- High mechanical properties<br>- High durability | - Other materials needed for a structure not easily available<br>- Very low salt content<br>- Much handwork<br>- Time consuming |
| **Temporary structures** | Salt and starch, ≥ 53% |  | - Additive manufacturing<br>- Time saving process<br>- Flexible design<br>- Thin structures possible | - Poor mechanical properties<br>- Referred to in literature only as non-load-bearing<br>- Soluble in water, needs special coating |
| | Crystalized salt, 100% |  | - Temporary structures (e.g. shading construction)<br>- Low Cost<br>- Indoor or outdoor application possible | - Low durability<br>- Application possible only in very dry, hot climate conditions near salt brine or salt lakes<br>- Soluble in water |
| **Interior floor** | Only salt, 100% | | - Easy to refill<br>- Cheap | - Hard to clean<br>- Soluable in water |

Table 4. Advantages and limitations of salt material application.

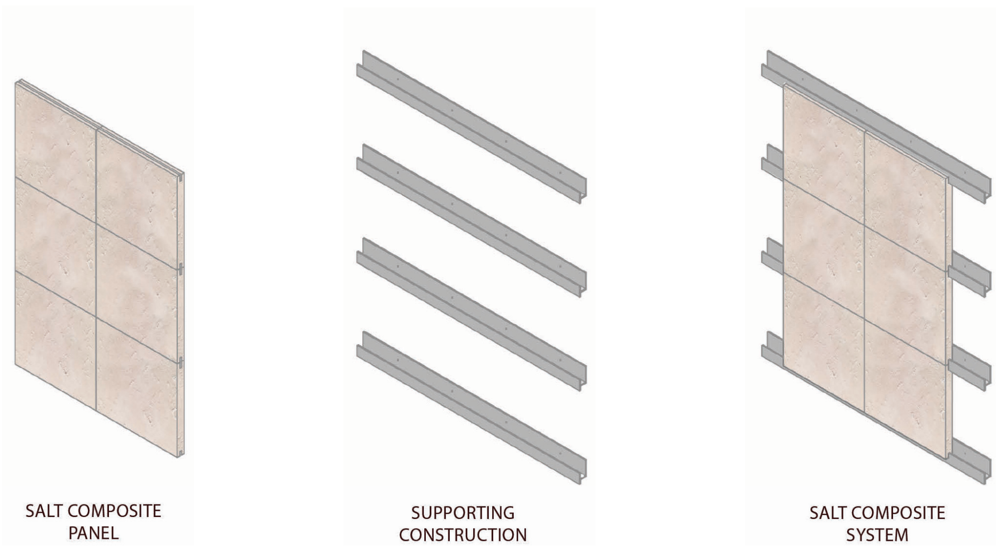



Figure 3. Salt composite system.

Figure 4. 3D printing with salt-clay paste.

## POSSIBILITIES CHALLENGES, AND FUTURE OPPORTUNITIES

The material properties of salt such as humidity and heat storage, compressive strength, and health issues are attractive for potential applications in the building sector. Composite salt materials show a wide variety of properties when mixed with clay, concrete, or starch. Karshif salt blocks have, in comparison to other CS materials, the highest salt content; mixtures between salt and starch allow utilization in 3D printing; Roman marine concrete is known for its high durability to withstand a marine environment; and, in comparison to commonly used concrete, salt concrete showed similarity in strength and heat capacity. The manufacturing processes of pressing, surface impregnation, and natural salt crystallization show interesting results in terms of humidity exposure and architectural applications such as shading systems.

Negative effects of salt such as dissolution at high environmental relative humidity, increasing porosity, reduction of compressive strength in some material mixtures, and negative experience with salt in masonry (efflorescence and deterioration) restrain its application. The properties of existing salt materials in the building sector have only been explored to a limited degree in the literature, which has concentrated mostly on the negative impacts of salt or on the protection of salt in building materials. Therefore, knowledge about the behavior and properties of salt is often limited, as studies have investigated only one or two properties without exploring their combination. A greater overview could lead to a better understanding of salt as a building material.

This paper is the first ever review of salt materials as building materials. This indicates that salt materials need to be further analyzed and the paper suggests several recommendations for future application:

(1) Salt mixed with other materials can increase the resource efficiency in building construction. Currently, REA gypsum represents around 50% of the gypsum used in Germany, but this resource will soon disappear because of the planned closure of the country's coal power plants. Therefore, mixing salt with gypsum or other materials could reduce the demand for energy-consuming or rare materials.
(2) Some salt materials (such as salt concrete and Karshif) can influence indoor environment conditions. Salt concrete can absorb and release heat from the air and could be used as a thermal storage material in climates with high day-night temperature differences. Karshif (salt-clay) can absorb and release the vapor from the air and could be used as a humidity storage material in climate conditions with short exposure to higher relative humidity.
(3) Salt materials with a higher amount of salt and increased efflorescence on the surface could positively affect human health in buildings. Emissions from salt materials could provide healthier working or living conditions. Salt is not toxic, is free of chemical emissions and has no odor.

(4) Raw salt materials or salt brines could be used for temporary building construction such as pavilions, exhibition construction, and shading systems of buildings and open areas. Temporary building structures in very hot and dry climate conditions could be built with the technique of salt crystal growth following seawater evaporation and could easily be demolished with water.
(5) Salt is not flammable and has good acoustic properties (in comparison with wood it has higher average bulk density). It could be used as infill material for walls in dry and hot climate conditions.
(6) Salt materials can be adapted to different building techniques (e.g., 3D printing, additive manufacturing, masonry, prefabrication).

## CONCLUSION

Salt has always played a significant role in human life. Recently, salt waste generated from the desalination and potash mining industries has started to encourage its re-use in different applications. This paper has explored the historical and future use of salt in the field of construction. Resource efficiency has become one of the major concerns in the construction industry and, despite some of the limitations of salt mentioned earlier, there is still potential with further technological advancement (3D printing, additive manufacturing, pressing, melting), and material research. In general, using salt waste is a promising solution for reducing the dependence on conventional materials such as gypsum or cement, creating healthier indoor environments, and reducing pollution.

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## A-2: Paper: Hygrothermal Performance of Salt (NaCl) for Internal Surface Applications in the Building Envelope

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*Article*

# Hygrothermal Performance of Salt (NaCl) for Internal Surface Applications in the Building Envelope

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**Abstract:** Salt (NaCl), as a by-product from the potash and desalination industry, can be the solution to the scarcity of building materials and might replace more energy-consuming materials. However, salt carries the risk of deliquescence in humid environments. This study conducted fundamental research on the hygrothermal performance of salt for internal surface applications in the building envelope in six different climate conditions. In addition, salt's performance was also compared with that of gypsum in similar applications. The simulation models (using WUFI®Pro, WUFI®Plus) and in situ measurements were applied to investigate the hygrothermal consequences of the incorporation of salt on the thermal envelope, indoor environment, and energy consumption. Our studies revealed that salt provided the best hygrothermal responses without Heating, Ventilation, and Air Conditioning (HVAC) in very hot-dry and the worst in very hot-humid climates. With an energy-efficient thermal envelope and HVAC, salt can also find an indoor application in temperate, continental, and subpolar climates. In comparison to gypsum, salt has a slightly higher energy demand (heating, cooling, and dehumidification) due to its higher thermal conductivity and moisture resistance. This study fills the knowledge gap on salt's hygrothermal performance and shows the potential in its utilization.

**Keywords:** salt; gypsum; hygrothermal performance; experiment; WUFI simulation

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## 1. Introduction

Newly built or retrofitted buildings are expected to be energy efficient [1,2], provide comfortable indoor room conditions for living [3], and be durable [1]. While new requirements are improving buildings' energy efficiency with higher airtightness and more insulation of the building envelope, the moisture content inside the buildings is increasing [1,4–6]. Too much moisture in the building envelope or too high relative humidity in the room air provide ideal conditions for mould growth [1], deterioration of the materials [7], as well as unsuitable indoor room conditions [3]. Various different strategies [8] have already been implemented in research and practice to counteract the moisture challenge, including energy-efficient building envelopes, controlled HVAC systems, improvement of occupant behaviour, and innovative building constructions [9].

In addition to these strategies, the selection of materials is an area of great interest, especially now, when the world population is growing [10] and the demand for building materials is increasing [11]. It is thus essential to identify new building materials that can substitute rare, expensive or energy-consuming materials that can contribute to better living conditions [12].

One of those potential materials is salt (NaCl), which is a by-product from the potash and desalination industries in a quantity of up to 3 billion m$^3$ per year [13,14]. Typically, salt waste is discharged directly into the environment where it causes negative impacts (change in salinity, increase in temperature, and loss of biodiversity) [15–28]. However, salt can have advantages as a building material in increasing resource efficiency; it is also antibacterial [19] and inflammable [19], has no odour [20], and can store humidity and heat [19,21,22]. In terms of health, salt caves and salt rooms across Europe have been shown to positively affect human lung cancer cells, depression, respiratory, and skin-related diseases [23–34]. Salt has already been used as a building material in the past [35–44]. Initially, buildings were built from solid salt blocks cut from nearby salt-rich lakes [35–37]. The Romans diversified the use of salt in construction, for example, by mixing seawater, volcanic ash, and lime to create a strong concrete [38,45]. In the last 60 years, salt has entered a new round of innovation including technological developments in compressing salt under pressure [46–49], 3D printing with salt [41–43,50], and using natural crystallization for new products (shading system or salt plates) [51,52]. In recent years, salt blocks from the Himalayas are starting to get more attention in the construction industry due to their high salt content (up to 98.30% [44]), workability, easy fixing systems, and translucency and have already been used in several restaurants and spas worldwide [53,54]. However, in contrast with more commonplace building materials, salt must be used with caution unless in very hot-dry climates or controlled indoor conditions [44]. Limitations in the use of salt stem from the solubility of salt crystals in water and at high relative humidities (more than 75.0%) [19,22], its corrosive action on steel [55], and its detrimental and efflorescent effects on bricks [56].

Salt can be incorporated into a wide range of materials and components [39–41,45] and limited studies on the use of salt in the field of construction have already been undertaken [21,39,57,58]. Most of the studies have been dedicated to studying the mechanical [39,58,59] or hygrothermal [21] properties of salt mixtures such as: karshif stone (salt and clay) and salt concrete (salt and concrete). Karshif stone is a material that can be still found in Siwa Oasis in Egypt [57,60]. It was designed by collecting salt pieces from the nearby salt sea, connected by salt–clay mortar, and under very dry climate conditions over many years formed into a stone [57]. Makhlouf and his team [21] examined the hygrothermal properties of this karshif stone (a salt block composed of up to 95.0% salt and enriched with clay and sand) and compared it with sandstone and limestone. They discovered that karshif stone can buffer moisture better than sandstone and limestone. The Deutsche Gesellschaft zum Bau und Betrieb von Endlagern für Abfallstoffe mbH (DBE) has defined the mechanical and thermal material properties of salt concrete mixture (54.0% salt and 46.0% concrete) for the safe disposal of radioactive waste in Morsleben, Germany [39]. The specific heat capacity (C) and heat conductivity ($\lambda$) of salt concrete were within a range of values for concrete and salt rock. However, the porosity was higher, and permeability and compressive strength lower, in comparison with commonly used concrete. A similar research project was conducted by Czaikowski and his team [58], who investigated the chemical–hydraulic behaviour of salt concrete in contact with saturated NaCl solution. Their experimental study of sealing systems for disposal of nuclear waste in Germany resulted in more or less identical material properties as those defined by DBE.

There are very few scientific studies about salt as a building material and usually, these have focused only on salt's material properties. Salt applications on the thermal envelope interior and hygrothermal characterization have not yet been explored. Applying salt as an interior finish to the building envelope can modify the hygrothermal performance of the exterior wall, which might result in a number of hygrothermal risks [1,3,61]. The increased water content in the wall construction and in the interior surface of salt material may exceed the critical relative humidity and water content of salt. The critical hygrothermal conditions found in the literature for salt are characterized by a water content of over 0.5% (5 kg/m$^3$) at relative humidity greater than 75.0% [55–57]. As long as the water content (moisture) and relative humidity in the pore system of salt remain above these critical values, condensation will occur and the salt crystals will dissolve [19,22]. Additionally, salt's higher vapour diffusion resistance factor (in comparison with gypsum) [62–64] might lower the temperature of the wall structure and change the drying time of the wall. Lastly, salt's potential influence on the indoor air quality (air relative humidity and air temperature) should be investigated since it can affect the comfort and health of building occupants.

## 2. Materials and Methods

The key aims of our study are to evaluate the moisture and heat performance of salt blocks for internal surface applications in the building envelope and to investigate their influence on room temperature and humidity in different climatic regions. To achieve this, we conducted hygrothermal simulations and on-site measurements. In the hygrothermal simulation, the relevant hygrothermal properties of the salt block were firstly defined, used as input values in the simulation, and compared with gypsum. On-site measurements were typically taken for 5 months to evaluate salt behaviour in real-life situations. Our research contributes to filling the knowledge gap on the risks and benefits of using salt in the thermal envelope, which helps to understand salt's potential as a building material and how it ages.

### *2.1. Hygrothermal Simulation*

#### 2.1.1. Objective

The transport of heat and moisture in the thermal envelope under natural weather conditions were simulated with WUFI®Pro, while the influences on the indoor air temperature and relative humidity were monitored with WUFI®Plus for 6 different climates. To compare the hygrothermic behaviour of the salt plate with that of a more typical interior finish, a sample with an internal gypsum plaster cladding was also studied. The WUFI®Pro simulation investigated the frequency of overstepping the critical boundaries and the impact on the hygrothermal process in the wall assembly/the interior surface of salt material in different climatic zones. WUFI®Plus simulations were carried out to define energy demand (cooling, heating, dehumidification, and humidification) and indoor air quality (see Figure 1).

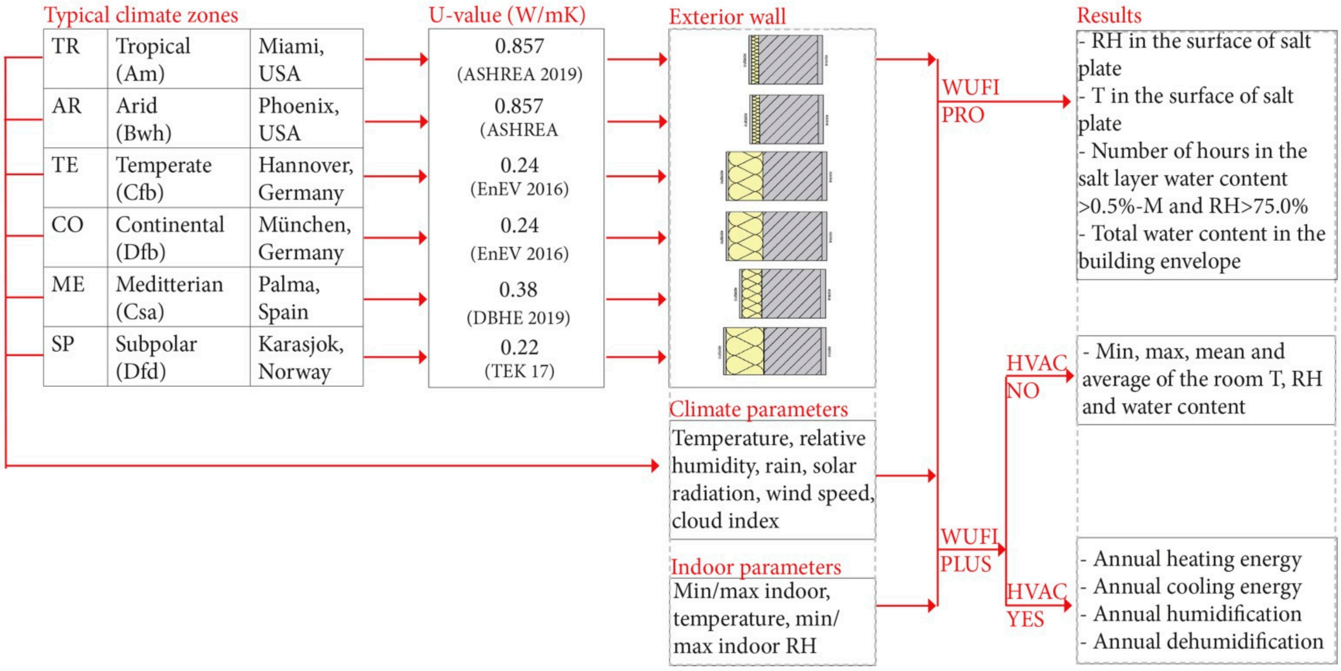



**Figure 1.** Simulation model design with the boundary conditions and expected results.

2.1.2. External Condition—Climate Parameters

External conditions (Table 1, Figure 2) were chosen across six different climate zones in Europe and North America, according to the Köppen climate classification. These locations were selected to investigate the most appropriate climatic conditions for salt materials. Meteorological data were defined in WUFI®Programs and consisted of annual outdoor air temperature, annual outdoor relative humidity, mean wind speed, solar radiation sum, and rainfall sum.

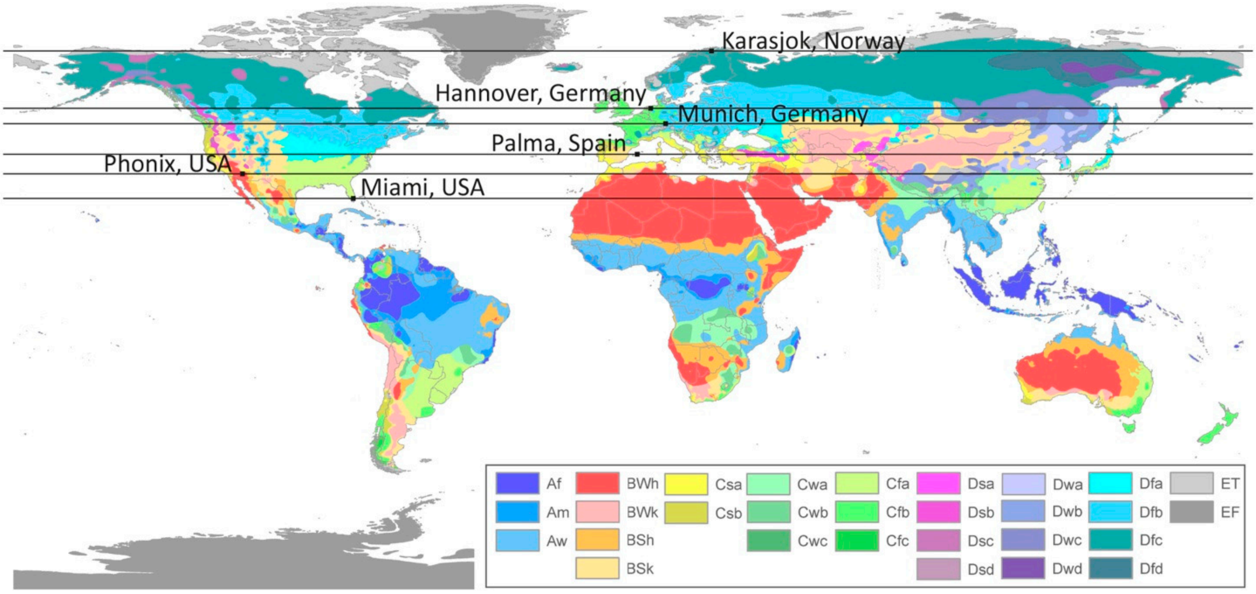



**Figure 2.** Six different climate zones in Europe and North America, according to the Köppen climate classification.

**Table 1.** Exterior weather conditions.

| | Climate Zones—Köpper–Geiger Climate Classification | City | Climate | Position (Latitude, Longitude) | U-Value Requirements (W/m²K) |
|---|---|---|---|---|---|
| TR | Tropical (Am) | Miami, USA | Monsoon | 25.80°N 80.27°W | 0.857 (ASHREA 2019) |
| AR | Arid (Bwh) | Phoenix, USA | Dessert, hot arid | 33.43°N 112.02°W | 0.857 (ASHREA 2019) |
| TE | Temperate (Cfb) | Hannover, Germany | Humid and warm summer | 52.37°N 9.37° E | 0.24 (EnEV 2016) |
| CO | Continental (Dfb) | Munich, Germany | Fully humid, cool summer | 48.13°N 11.72°E | 0.24 (EnEV 2016) |
| ME | Meditterian (Csa) | Palma, Spain | Dry summer, hot summer | 39.56°N 2.65°E | 0.38 (DBHE 2019) |
| SP | Subpolar (Dfd) | Karasjok, Norway | Fully humid cold summer | 69.47°N 25.49°E | 0.22 (TEK 17) |

2.1.3. Internal Conditions—Indoor Parameters

The internal simulation conditions in WUFI®Pro were obtained by standard values from the WUFI database. The indoor conditions in WUFI®Plus varied: at first, the HVAC was turned off to evaluate the influence of the climate zone and construction on the indoor temperature and relative humidity. In the next step, the HVAC was turned on, to maintain the indoor air quality standards and to evaluate the energy demand (annual heating and cooling, humidification, and dehumidification). Table 2 lists the various hygrothermal impact indicators.

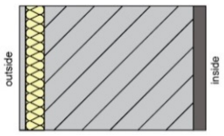
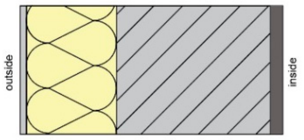
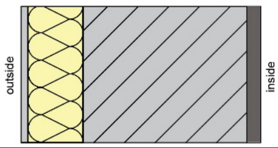
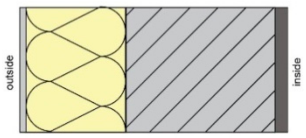
**Table 2.** Outdoor and indoor conditions for the simulation model.

| | **WUFI®Pro** | **WUFI®Plus** |
|---|---|---|
| Outdoor condition (weather data) | Real weather data from the WUFI®Pro/Plus programme | Real weather data from the WUFI®Pro/Plus programme |
| Indoor condition | USA: ASHRAE 160<br>Europe: EN 15026, DIN 4108, WTA 6-2 | USA: ASHRAE 160<br>Europe: EN 15026, DIN 4108, WTA 6-2 |
| Component (wall/room) | Thermal envelope | Room (3 m × 3 m × 3 m) |
| Calculation Period, Profiles | 3 Years<br>(time steps: 1 h) | 1 year<br>(time steps: 1 h) |
| Orientation | Wall component is oriented to north (the lowest solar radiation) | No windows to evaluate the influence of the climate zones and construction |
| Inclination | 90° | 90° |
| Initial moisture and temperature in construction component | RH = 70.0%<br>T = 20 °C | RH = 70.0%<br>T = 20 °C |
| Driving Rain Coefficients | 0.07 | 0.07 |
| Monitor Position | Material surface | In a room |
| Number of occupants | 1 person per room | 1 person per room |
| Office indoor heat and moisture load | Standard program input | Convective heat: 33.3 W<br>Radiant heat: 25.2 W,<br>Moisture 17.55 g/h,<br>$CO_2$: 20.79 g/h<br>Human activity: 1.2 met<br>Air velocity: 0.1 m/s |
| Clothing | Standard program input | 0.7 clo |
| Occupancy Period | Standard program input | 7.00–18.00 |
| Energy system | Only heating<br>Depending on the climate zone<br>(norms: EN 15026, DIN 4108, WTA 6-2, ASHRAE 160) | HVAC on:<br>Indoor air temperature 21–27 °C<br>RH 40.0–70.0%<br>Max $CO_2$: 3000 ppmv<br>Air exchange: 0.6 $h^{-1}$<br>Heating, cooling, humidification, and dehumidification calculated<br>HVAC off |

#### 2.1.4. Boundary Condition—Exterior Wall

The simulation models used a masonry construction typical in Germany with different thicknesses of external thermal insulation composite system (ETICS) (Table 1). The ETICS thickness was defined according to the locally permitted maximal heat transfer coefficient U-value of the specific climate zone (see Table 3). The simulation model (exterior wall) comprised of four main layers: (1) an outdoor render, (2) a thermal insulation, (3) a brick construction, and (4) an indoor plaster (salt or gypsum). Salt was always simulated and compared with the gypsum for a better understanding of the salt's performance. The salt material analysed was Himalayan salt rock [53,65], which is the most common salt material in the construction industry, fixed in place with various techniques (glued on interior walls, hung on a secondary mesh construction, or connected with steel profiles) [54]. The hygrothermal properties of this salt rock could not be found in the literature and were, therefore, for the goals of this research, analysed at Fraunhofer Institut IBF, Germany in 2020 [62,63]. The relevant properties for the hygrothermal simulation of all other materials, used as input data in WUFI®Pro and WUFI®Plus, are presented in Table 3.

**Table 3.** Boundary condition (construction of the exterior walls with the material properties). The indoor material layer is gypsum or salt (dark grey).

| **Construction from Outside to Inside (cm)** | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | **U-Value ($W/m^2K$)** | **Mineral Plaster** | **Mineral Insulation Board** | **Solid Brick Masonry** | **Gypsum Plaster** | **Salt** |
| Wall 1: Tropical (TR) and arid (AR) climate zone |   | 0.72 (gypsum) | 1.0 | 3.0 | 24.0 | 2.0 | |
| | | 0.77 (salt) | 1.0 | 3.0 | 24.0 | | 2.0 |
| Wall 2: Temperate (TE) and continental (CO) climate zone |   | 0.23 (gypsum) | 1.0 | 14.0 | 24.0 | 2.0 | |
| | | 0.24 (salt) | 1.0 | 14.0 | 24.0 | | 2.0 |
| Wall 3: Mediterranean (ME) climate zone |   | 0.35 (gypsum) | 1.0 | 9.0 | 24.0 | 2.0 | |
| | | 0.35 (salt) | 1.0 | 9.0 | 24.0 | | 2.0 |
| Wall 4: subpolar (SP) climate zone |   | 0.21 (gypsum) | 1.0 | 16.0 | 24.0 | 2.0 | |
| | | 0.22 (salt) | 1.0 | 16.0 | 24.0 | | 2.0 |
| **Material properties** | | | | | | | |
| Bulk density ($kg/m^3$) | | | 1900 | 15 | 1900 | 850 | 2087 |
| Porosity ($m^3/m^3$) | | | 0.24 | 0.95 | 0.24 | 0.65 | 0.04 |
| Specific Heat Capacity (J/kgK) | | | 850 | 1500 | 850 | 850 | 850 |
| Water Vapour Diffusion Resistance Factor (-) | | | 25 | 30 | 10 | 8.3 | 7836 |
| Thermal conductivity (W/mK) | | | 0.8 | 0.04 | 0.6 | 0.2 | 2.65 |
| Typical Build-In Moisture ($kg/m^3$) | | | 210 | 44.8 | 100 | 400 | 999 |

### *2.2. Experimental Measurements*

#### 2.2.1. Objective

We took experimental measurements to investigate the hygrothermal impact of salt, gypsum, and salt–gypsum in a temperate climate. The relative humidity and the materials' temperatures were tested over five months in Munich, Germany. The measured results were then compared with the simulation models.

#### 2.2.2. The Testing Room

The monitoring was carried out in a room in a typical existing 1980s residential building in Munich, Germany (48°10′ N, 11°32′ E) [9]. The room has three internal and one external walls (Figure 3). The investigated part of the room was the external wall, composed of a brick wall with poor thermal insulation, almost no wind exposure, and southwest orientation. This existing wall is made up of four layers (Figure 2) and during the day is shaded 70.0% of the time by vegetation, balconies, and surrounding buildings in the summer and 80.0% of the daytime in the winter. Four people live in the apartment, but the test room was mostly used by just two. The room's interior conditions are not totally controlled and represent rather typical living conditions of a family with varying room occupancy, with heating in winter and shading in summer, together with influences from other rooms.

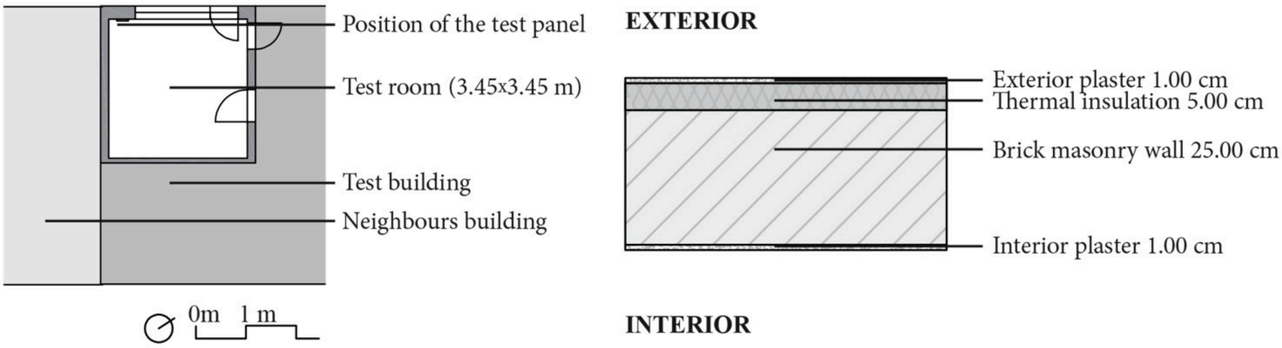



**Figure 3.** (**Left**): Ground plan of the test room. (**Right**): Exterior wall of the testing room.

2.2.3. The Test Materials

One test panel (Figure 4) comprised of three different materials was placed on the indoor surface of the exterior wall. It consists of a 29.0 cm × 78.0 cm timber frame filled with samples of the three materials of 20 cm × 20 cm × 2.5 cm size. From the top down, these materials are: pink rock salt, gypsum, and salt–gypsum. The material characteristics of the salt plate and gypsum are shown in Table 3. Boundary condition (construction of the exterior walls with the material properties). The salt–gypsum sample is a mixture of 70.0% gypsum and 30.0% salt: however, its material properties were not tested. The joints between the test materials and the timber frame were filled with silicone paste, while the fixing of the frame to the wall was made airtight with sealing tape. Nevertheless, we assume that the temperature difference between the internal and external surfaces of the material samples and sealing deformation cannot provide total control of moisture and temperature flow.

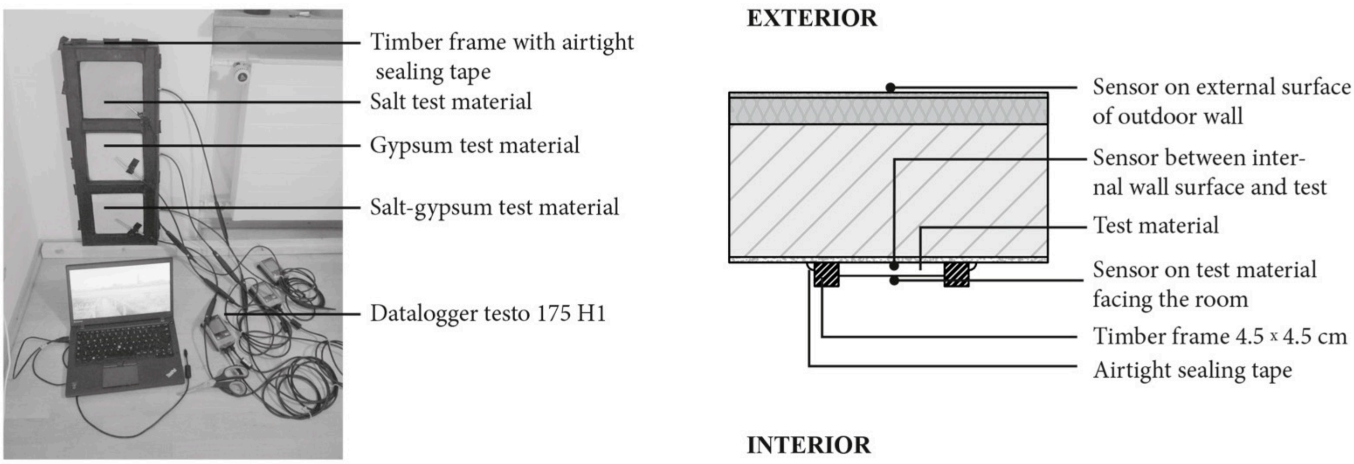



**Figure 4.** (**Left**): Test panel. (**Right**): Horizontal section through the test panel installation.

2.2.4. The Test Instrumentation

Temperature and relative humidity from Testo were installed at the centre of each sample material surface to measure relative humidity and temperature. One sensor was installed on the centre of the outer surface facing the room, the second sensor was installed on the centre of the interface between the surface of the material and the inner surface of the external wall, and the third sensor was installed on the outer surface of the external wall (Figure 4). Indoor environment conditions were measured with temperature and relative humidity sensor 176 H1 in the middle of the room at 1.8 m height.

Outdoor environment temperature and relative humidity values were taken from the real weather condition. All the sensors were calibrated by the manufacturers and the accuracy ranges are shown in Table 4.

**Table 4.** Sensors.

| Sensors | Accuracy Ranges |
| --- | --- |
| testo 176 H1—Temperature and humidity data logger (data logger for sensors on the test materials) | ±0.2 °C (−20 to +70 °C) ±1 Digit<br>±0.4 °C (Remaining Range) ±1 Digit<br>dependent on probe selected (0.0 to 100.0% RH) |
| Thin humidity/temperature probe with cable (sensors on the test materials) | ±0.2 °C at 0 to +40 °C<br>±2.0% RH at +25 °C (2.0 to +98.0% RH)<br>±0.08% RH/K (k = 1), long-term stability: ±1.0% RH/year |
| testo 175 H1—Temperature and humidity data logger (exterior and interior measurements) | ±0.4 °C (−20 to +55 °C) ±1 Digit at −20 to +55 °C<br>±2.0% RH (2.0 to 98.0%) at +25 °C<br>±0.03% RH/K ±1 Digit<br><±1.0% RH/year drift at +25 °C |

2.2.5. The Test Protocol

The duration of the monitoring was about 139 days (from 2 August 2020 till 18 December 2020), which covered the three climate conditions: hottest (summer), moderate (autumn), and coldest periods (winter). In view of the manufacturer's recommendation for monitoring salt materials with steel sensors, their data were collected for less than 6 months. Data from the sensors on the interior wall, the test panel, and the exterior wall surface were saved every 10 min during the testing period. The interior temperature and humidity in the test room were not controlled. It changed according to its occupancy level, the heating period, the extent of shading to the window, and the infiltration of air through the doors and windows.

## 3. Results

### *3.1. Simulation WUFI®Pro*

Tables 5 and Figure 5 show the values of the hourly simulated relative humidity (RH), temperature (T), and water content (WC) for the indoor surface (gypsum—G and salt S) and for the exterior wall construction for each climate (TR—Tropical, AR—Arid, TE—Temperate, CO—Continental, ME—Mediterranean, and SP—Subpolar). Minimum, maximum, average, and mean values of temperature, relative humidity, and water content are listed in Table 5 to show the differences in climate zones as well as the comparison between salt and gypsum. The higher the temperature and relative humidity in a climate zone, the higher the T, RH, and WC in the observed materials.

Figure 5 shows the water content and RH over three years in the gypsum (G) and salt (S). The differences in RH in both materials are negligible compared to the water content. The water content in gypsum is more variable over time than in salt and shows a slight water uptake during the three years in all climate zones.

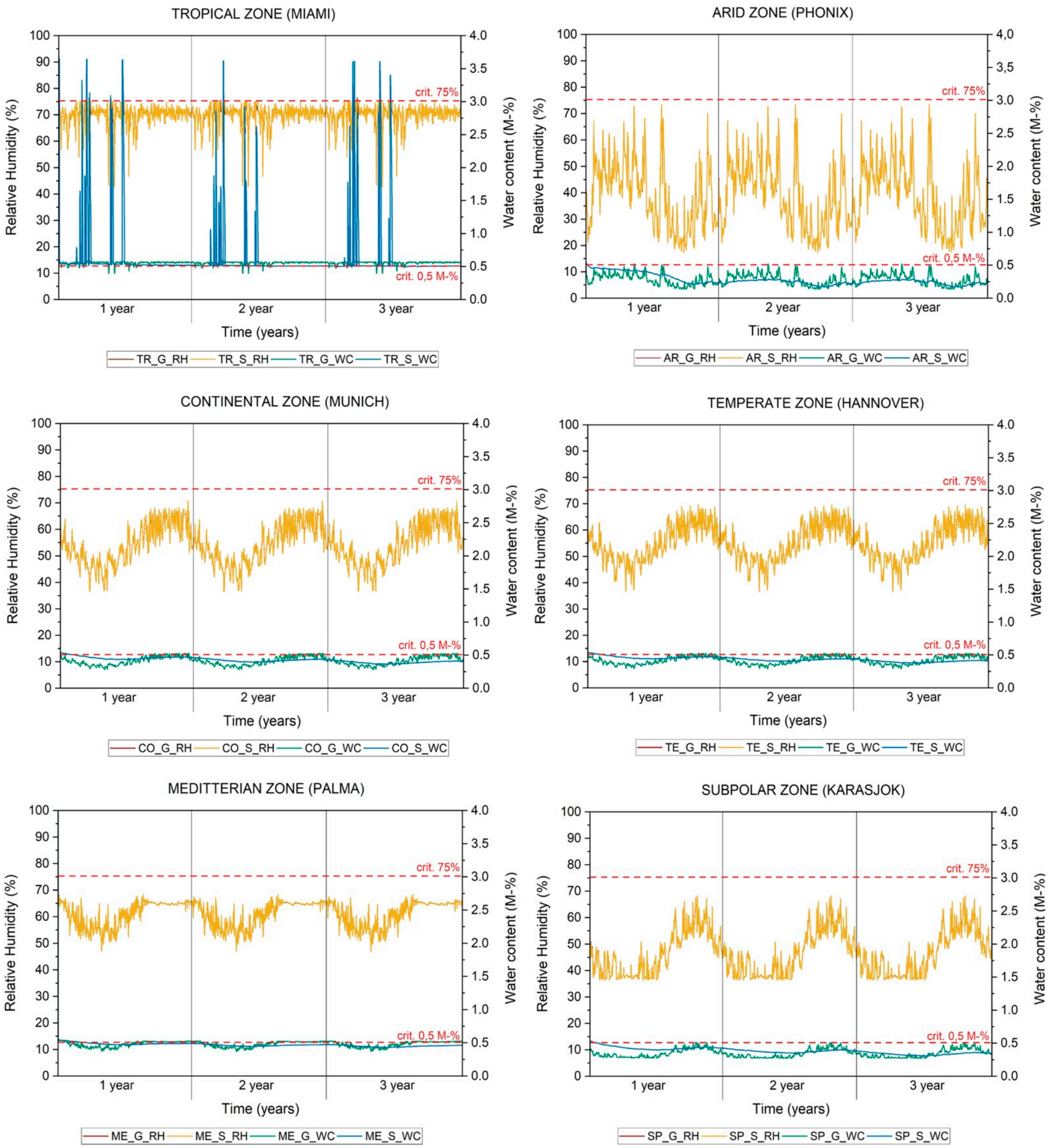



**Figure 5.** Simulated RH and water content of salt and gypsum over three years (G_RH—gypsum and relative humidity, S_RH—salt and relative humidity, G_WC—gypsum and water content, S_WC—salt and water content).

**Table 5.** The characteristics of the simulated relative humidity, temperature, and water content in gypsum/salt and the water content in the whole exterior wall in different climate conditions: the minimum, the maximum, the average, and the mean range.

| | TR_G | TR_S | AR_G | AR_S | CO_G | CO_S | TE_G | TE_S | ME_G | ME_S | SP_G | SP_S |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Relative Humidity, Surface (%)** | | | | | | | | | | | | |
| Min | 43.85 | 42.68 | 17.58 | 17.38 | 36.95 | 36.60 | 36.94 | 36.62 | 47.19 | 46.95 | 36.61 | 36.31 |
| Max | 89.02 | 99.61 | 71.53 | 73.50 | 68.64 | 70.77 | 68.11 | 69.65 | 74.53 | 76.11 | 66.68 | 68.30 |
| Ave | 69.81 | 70.17 | 38.92 | 39.02 | 54.27 | 54.27 | 54.80 | 54.84 | 61.04 | 61.08 | 46.37 | 46.42 |
| Mean | 70.76 | 70.92 | 38.80 | 38.83 | 53.80 | 53.74 | 54.34 | 54.32 | 62.73 | 62.91 | 45.81 | 45.77 |
| **Water Content, Surface (kg/m³)** | | | | | | | | | | | | |
| Min | 3.95 | 4.95 | 1.33 | 1.66 | 2.82 | 3.64 | 2.91 | 3.79 | 3.69 | 4.29 | 2.72 | 3.07 |
| Max | 6.83 | 36.52 | 5.23 | 5.40 | 5.32 | 5.41 | 5.40 | 5.42 | 5.69 | 41.01 | 5.19 | 5.38 |
| Ave | 5.57 | 6.47 | 2.84 | 2.77 | 4.14 | 4.25 | 4.18 | 4.33 | 4.81 | 4.69 | 3.45 | 3.83 |
| Mean | 5.63 | 5.12 | 2.85 | 2.59 | 4.10 | 4.25 | 4.13 | 4.31 | 4.97 | 4.68 | 3.34 | 3.81 |
| **Salt (Water Content > 0.5 kg/m³ and RH > 75.0%), Gypsum (T = 5–40 °C and RH > 80.0%) (1st year, 2nd year, 3rd year)** | | | | | | | | | | | | |
| Hours | 19.0, 0.0, 0.0 | 414.0 196.0, 402.0 | 0.0, 0.0, 0.0 | 0.0, 0.0, 0.0 | 0.0, 0.0, 0.0 | 0.0, 0.0, 0.0 | 0.0, 0.0, 0.0 | 0.0, 0.0, 0.0 | 0.0, 0.0, 0.0 | 2.0, 0.0, 0.0 | 0.0, 0.0, 0.0 | 0.0, 0.0, 0.0 |
| **Temperature, Surface Layer (°C)** | | | | | | | | | | | | |
| Min | 20.51 | 19.95 | 19.71 | 19.56 | 19.05 | 19.03 | 19.18 | 19.16 | 19.24 | 19.20 | 18.54 | 18.50 |
| Max | 32.43 | 32.40 | 41.47 | 41.43 | 24.88 | 24.88 | 24.82 | 24.83 | 25.20 | 25.23 | 23.99 | 23.95 |
| Ave | 27.73 | 27.68 | 28.20 | 28.17 | 20.78 | 20.77 | 20.77 | 20.75 | 22.56 | 22.55 | 19.66 | 19.65 |
| Mean | 27.86 | 27.79 | 28.14 | 28.13 | 19.65 | 19.64 | 19.70 | 19.69 | 22.88 | 22.85 | 19.43 | 19.42 |
| **Water content, whole construction (kg/m²)** | | | | | | | | | | | | |
| Min | 2.81 | 2.36 | 0.39 | 0.38 | 1.68 | 1.51 | 1.78 | 1.59 | 2.15 | 1.95 | 1.65 | 1.34 |
| Max | 3.58 | 3.83 | 3.17 | 3.16 | 3.47 | 3.63 | 3.33 | 3.49 | 3.52 | 3.95 | 3.30 | 3.56 |
| Ave | 3.10 | 2.71 | 0.98 | 0.92 | 2.20 | 2.32 | 2.26 | 2.43 | 2.53 | 2.53 | 2.08 | 2.42 |
| Mean | 3.11 | 2.65 | 0.98 | 0.73 | 2.16 | 2.19 | 2.23 | 2.31 | 2.47 | 2.46 | 1.97 | 2.51 |

### *3.2. Simulation WUFI®Plus—Influence on the Indoor Air Quality and Energy Consumption*

Figure 6 presents the dynamically simulated data of indoor air temperature and air relative humidity for gypsum and salt without HVAC (Heating, Ventilation, and Air Conditioning). The differences in the values can be attributed to the outdoor environmental influences and material parameters. The main differences (between G and S) are in relative humidity and not in temperature. The enclosed space with salt shows, in a comparison with gypsum, the lower range and, in most of the cases, a lower average RH value.

The annual energy consumption (cooling, heating, dehumidification, and humidification) with respect to outdoor environmental conditions for G and S are presented in Figure 7. These results help us understand how different surface materials influence energy consumption in various climate conditions. The result of the material influence is that in all climate zones, no energy for humidification is needed and that in most cases (13 out of 15), salt performs with a slightly higher energy demand in comparison with gypsum.

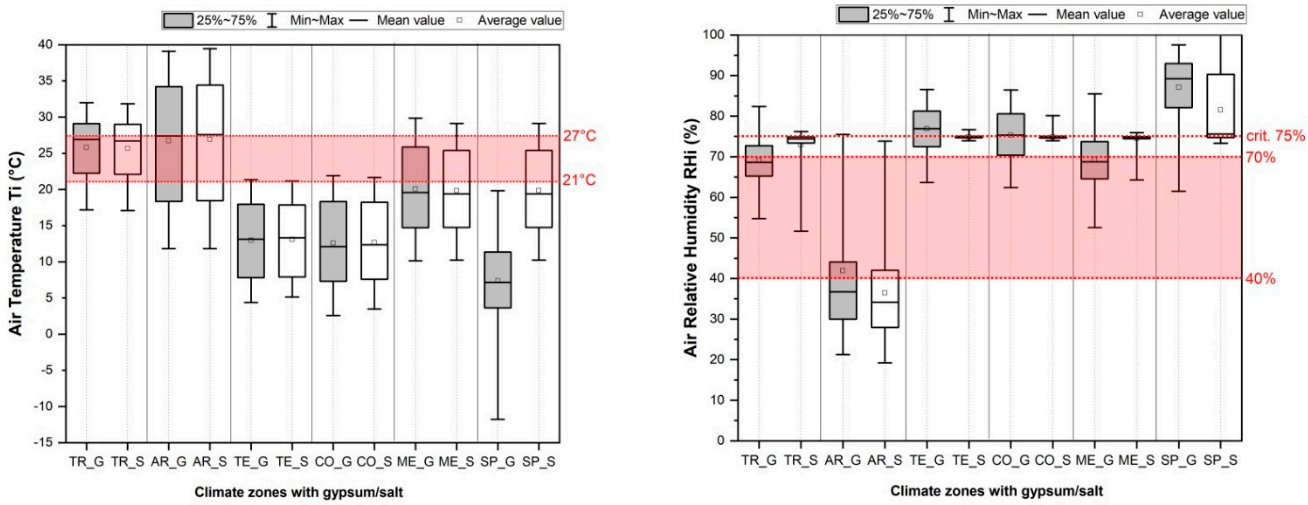



**Figure 6.** Simulated indoor air temperature and relative humidity for 6 climate zones (TR—Tropical, AR—Arid, TE—Temperate, CO—Continental, ME—Mediterranean, SP—Subpolar) with gypsum (G-grey box) or salt (S-white box) without HVAC. Red area – area for the most comfortable T (°C) and RH (%)

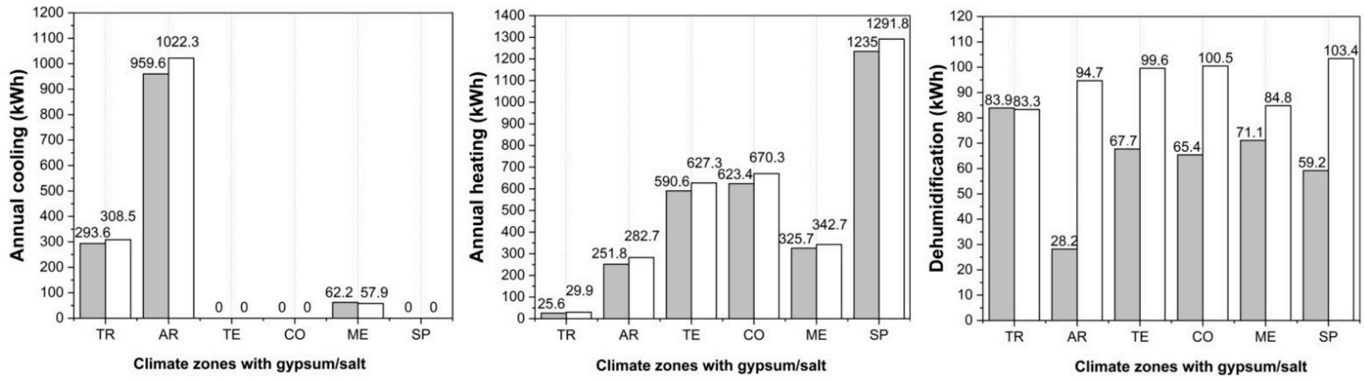



**Figure 7.** Comparison of annual cooling, heating, and dehumidification demand for gypsum and salt in six climate zones (TR—Tropical, AR—Arid, TE—Temperate, CO—Continental, ME—Mediterranean, SP—Subpolar, grey—gypsum, white—salt).

### *3.3. Measurements*

Figure 8 and Table 6 show the relative humidity and temperature of in situ measurements in the CO climate zone (Munich) for three materials (G—gypsum, S—salt, and SG—salt–gypsum). Each box shows the highest, lowest, mean, and average values.

**Table 6.** In-Situ measurements of relative humidity (RH) and temperature (T) on the interior (In) and exterior (Ext) surface of three materials (S—salt, G—gypsum, SG—salt–gypsum).

| | S_In RH | S_In T | S_Ext RH | S_Ext T | G_In RH | G_In T | G_Ext RH | G_Ext T | SG_In RH | SG_In T | SG_Ext RH | SG_In T |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Min | 33.46 | 18.90 | 33.31 | 18.40 | 39.93 | 18.91 | 41.24 | 18.57 | 41.97 | 18.84 | 3817 | 18.57 |
| Max | 70.86 | 24.99 | 68.11 | 24.76 | 72.72 | 25.06 | 68.25 | 24.91 | 73.21 | 24.82 | 69.00 | 24.65 |
| Ave | 50.72 | 21.90 | 49.70 | 21.52 | 55.01 | 22.63 | 54.52 | 23.00 | 55.42 | 21.54 | 52.74 | 21.74 |
| Mean | 50.01 | 21.88 | 49.43 | 21.46 | 54.27 | 22.88 | 53.46 | 23.52 | 54.21 | 21.45 | 52.71 | 21.69 |

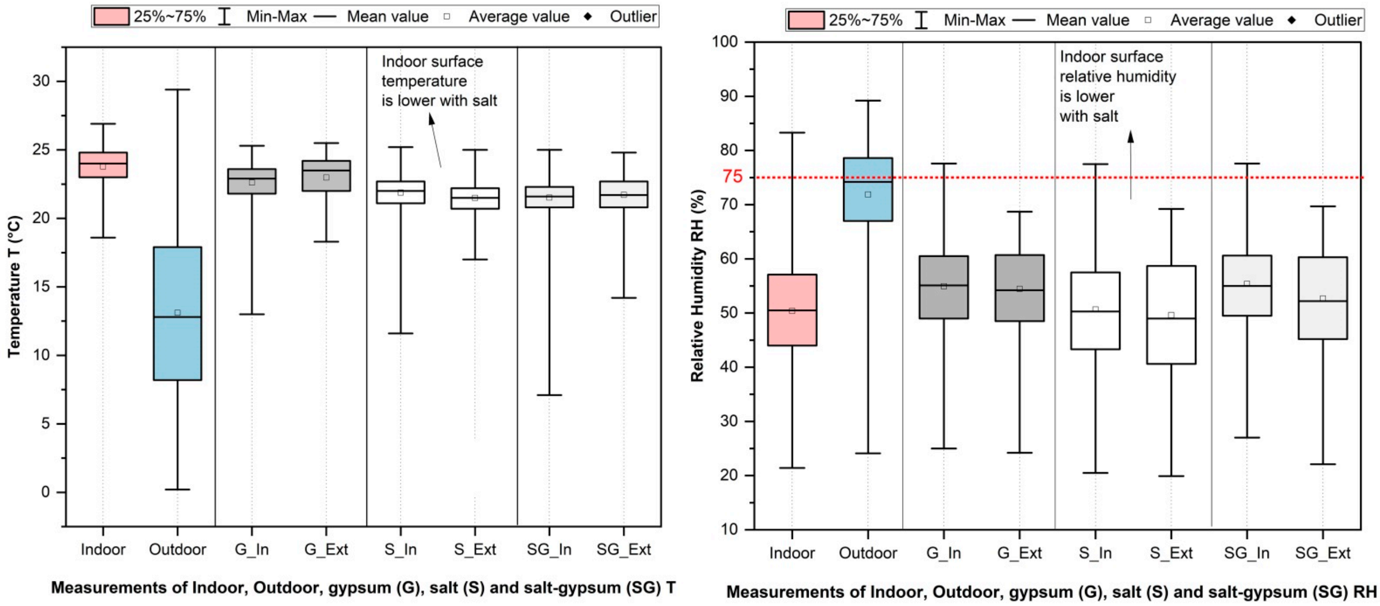



**Figure 8.** In situ measurements of relative humidity and temperature in Munich (red colour—indoor air temperature, blue colour—outdoor air temperature, grey colour—gypsum, white colour—salt, light grey colour—salt–gypsum, In—surface to interior, Ext—surface to exterior).

## 4. Discussion

Measured and simulated data for materials are discussed with respect to three topics: temperature, relative humidity, and water content, and influence on the indoor air quality and energy consumption. For a better interpretation of the performance of salt, gypsum values are set as reference models and compared with salt.

### *4.1. Temperature*

Salt (S), in comparison to gypsum (G), shows a reduction in the temperature of the surface of the internal walls. As can be seen in Tables 5 and 6, the measured and simulated average surface temperatures of salt are, in all climate zones, slightly lower than those of gypsum. According to the simulated results for all climate zones, the average temperature decreases up to a maximum of 0.05 °C in the TR zone (from 27.73 °C to 27.68 °C). According to the measured results (S) in the CO climate zone, the indoor surface temperature decreases by 0.73 °C (from 22.3 to 21.90 °C), which is 0.01 °C higher than in the CO simulation (from 20.78 to 20.77 °C). As can be seen in Figure 8, the measured average surface temperature of the salt–gypsum (SG) of the outer surface to indoor, and of the centre of the interface between the surface of the material and the inner surface of the external wall, is between the values of salt and gypsum. In general, the T of salt (S) is found to be lower in measured and simulated results. There is a small difference in values due to different periods of examination, and indoor and outdoor boundary conditions. With the higher thermal conductivity of salt, heat in salt is more rapidly transferred (than in gypsum) and, thus, has a slightly lower surface temperature.

### *4.2. Humidity and Water Content*

In the first step, relative humidity and water content in salt and gypsum are analysed, and the frequency by which the limits specified for salt are exceeded is defined (Table 5). The annual moisture balance of the whole envelope is then analysed through simulation for three years (Figure 5). In comparison to gypsum, salt shows an increase in RH. According to the simulated results for all climate zones, the average RH in the indoor surface layer of salt increases up to a maximum of 0.36% in TR (from 69.81% to 70.17%) and at the same time exceeds the RH limits. According to the measured results for salt in the CO climate zone, the RH of the outer surface of the salt test material decreases by 4.26% (from 55.01% to 50.72%). However, the simulation values show no difference. Mixing salt with gypsum (Table 6) shows also a decrease in the moisture resistance, and the measured average relative humidity of salt–gypsum increases up to a maximum of 3.04% (in comparison to salt). Only a slight difference in the relative humidity obtained for salt and gypsum was found during the three years of the simulation period (see Figure 5).

According to the simulated results for salt in all climate zones (Table 5), the average accumulated water content on the indoor surface, compared to gypsum, decreases up to a maximum of 0.12 kg/m$^3$ in the ME zone (from 4.81 to 4.69 kg/m$^3$) and increases up to a maximum of 0.40 kg/m$^3$ in SP (from 3.43 to 3.83 kg/m$^3$). Observing the results during the three-year period (see Figure 5) in different climate zones, the highest accumulated moisture content is found in salt in the TR and ME zones. The accumulated moisture content exceeds the critical limits specified for salt for 414 h in the first year, 196 h in the second year, 402 h in the third year in the TR zone, and 2 h in the first year in the ME zone. Both findings show the high risk of salt deliquescence, which is also present in the controlled indoor environment. The reason for this is the low u-value of the building envelope systems and high air humidity of this climate zone (a drying period does not occur or is too short), so the moisture remains in the material. As a general observation, it is noted that the water content values in salt in other climate zones are higher at the beginning of the period (first year) due to some initial moisture, decrease over time, and do not vary as dramatically as in gypsum, where the values fluctuate substantially with the smallest change in air RH or T.

With respect to the water content in the whole building envelope, the difference between S and G is not significant (up to a maximum of 14.0% in the SP zone). Building envelopes with salt show higher average water content in CO (5.0%), TE (7.0%), and SP (14.0%) zones and lower in TR (9.6%) and AR (6.0%) zones and the same values in the ME zone. The highest average water content (2.71 kg/m$^2$ for salt) is observed in building envelopes in the hot-humid climate zone (TR) and the lowest (9.92 kg/m$^2$) in the hot-dry climate. Due to the lower porosity and higher vapour diffusion resistance factor of salt (in comparison to gypsum), the high water content from construction cannot be transported as quickly towards the outdoor surface and thus dry out. In general, the smaller the insulation thickness, at a lower RH/T, the lower the relative humidity and water content of the thermal envelope. Salt is most appropriate for applications in hot-dry climates due to its lowest risk for moisture-induced damage and, therefore, higher durability of the building envelope in such climates.

### *4.3. Influence on the Indoor Air Quality without HVAC for Enclosed Spaces*

The corresponding comfort range for indoor air temperature (Ti) is in the range of 21–27 °C and relative humidity (RHi) in the range of 40.0–70.0%. The simulation results (Figure 6) for a building envelope with salt with no HVAC show the average Ti as appropriate at 25 °C in the TR and 26.9 °C in the AR zones, but inappropriate at 13.09 °C in CO, 12.66 °C in TE, 19.85 °C in ME, and 19 °C in the SP zone. The average Ti with salt decreases in comparison to gypsum by up to 0.12 °C in TR (25.80 to 25.68 °C) and by 0.15 °C in ME zones (20.08 to 19.85 °C). Average Ti with salt increases in comparison to gypsum by up to 0.81 °C in AR (26.12 to 26.93 °C), 0.08 °C in CO (12.58 to 12.66 °C), 0.11 °C in TE (12.98 to 13.09 °C), and 11.27 °C in SP (7.73 to 19 °C). So, evaluating the average indoor air temperature of the enclosed space, salt shows advantages compared with gypsum in the no HVAC conditions (in four of the six climate conditions the average Ti was higher) due to the higher thermal conductivity of salt that transmits the heat quickly from outside to inside.

Figure 6 shows also the average, min, max, and mean RHi for salt and gypsum in all climate zones with no HVAC. The average RHi for salt enclosed spaces is inappropriate in all climate zones (72.93% in TR, 36.45% in AR, 74.84% in TE, 74.85% in CO, 74.54% in

ME, and 82.0% in SP). All climate zones with an average RHi between 70.0 and 75.0% and a maximum > 75.0% in settings without HVAC are inappropriate for salt application due to the higher risk of deliquescence. Therefore, only AR climate zones with lower RHi are suitable for salt applications. The average RHi in salt enclosed spaces has lower values of the variation in comparison to gypsum, and in four of six cases also a lower average RHi. This is due to the higher water vapour diffusion resistance factor of salt (compared to gypsum) that does not absorb so much of the indoor RH and, thus, slightly reduces the humidity buffering ability of the building envelope to regulate variations in the indoor RH levels.

### *4.4. Influence on the Energy Consumption with HVAC for Enclosed Spaces*

The measured annual energy (Figure 7) use for the heating, cooling, and dehumidification presents data for the enclosed unit, both for the gypsum and salt applications. The salt enclosed space shows an annual increase in cooling demand of 4.8% in TR, 6.0% in AR, and a decrease of 6.9% in the ME zone. The annual heating demand for the salt enclosed space is higher in all zones with a maximal increase of 14.3% in the TR zone. In addition, the annual dehumidification demand for salt is higher in five of the six climate zones in comparison to gypsum. The results show that in hot-humid climate zones where there is great external heat or moisture load, the moisture and heat are transmitted through the building envelope from outdoor to indoor. In contrast, in cold climate zones with higher internal heat or moisture, the heat and moisture flow from inside to outside. The higher thermal conductivity, lower porosity, and higher bulk density of salt enable the quicker transport of heat and increase the annual demand for heating or cooling. The higher moisture resistance of salt prevents the transport of indoor humidity and increases the indoor dehumidification consumption due to interior heat gains. In future studies, it will be important to also have the real measured data for energy consumption of salt and gypsum. This would help to improve the simulation accuracy and make more accurate recommendations for salt.

### *4.5. Suggestions for Future Studies*

This research is the first-ever hygrothermal study of salt (Himalayan) as a building material for indoor application in six different climate zones. The hygrothermal performance of salt showed the potential to replace gypsum, especially in hot-dry climates. However, the knowledge gained in the study about salt's hygrothermal behaviour is limited, as it only investigated only one salt material. Therefore, the paper gives several suggestions for future studies:

- Salt mixtures with other materials for increasing resource efficiency and saving of $CO_2$: The annual world production of cement is about 4.4 billion tons [66], of gypsum 150 million tons [67–69], and 1.1 billion tons of salt [70–73] is produced each around the world. The production of cement and gypsum is subject to substantial criticism because of its high energy demand [74,75] and the heavy impact of mining on landscapes [15,17,76–78]. Resources such as FGD gypsum, which currently supply approx. 50.0% of the gypsum requirement in Germany [69], is disappearing due to German energy strategies (the phasing out of coal combustion) [79,80]. By increasing the salt content in the composite material, natural resources (e.g., natural gypsum) will be protected, less energy will be needed for production and $CO_2$ emissions will be reduced. Each ton of cement replaced by one ton of salt would save approximately 600 kg of $CO_2$ [81] emissions.
- Hygrothermal performance of other salt composites: The simulated and on-site measurements of different salt composites (salt and concrete, salt and gypsum, salt and clay) should be analysed in detail, comparing and evaluating the passive regulation of indoor temperature and relative humidity in different climate conditions.

The inclusion of other additives should also be considered for more effective heat and moisture transport.

- Durability of salt materials: Salt materials should be exposed to different humidity, temperature and different positions in the thermal envelope to investigate degradation, aging, and durability. Measured results should be compared with simulations.
- Other constructive possibilities: In this research was salt analysed only as a cladding element. Different constructive possibilities, such as supporting components in 3D printing, modular prefabricated elements, or just filling material for interior walls, should be further considered and explored.

## 5. Conclusions

This paper presents an investigation into salt's hygrothermal performance as an indoor building component of the thermal envelope, which is compared with a reference material (gypsum) in terms of six different typical climate zones, construction types, and HVAC.

A comparison between salt and gypsum shows that salt has higher bulk density, lower porosity, lower moisture storage, higher heat transport properties, and the same heat storage capacities as gypsum. As the simulation results of the building envelope (WUFI®Pro) show, the salt material layer has, in comparison to gypsum: a max. 0.05 °C decrease in the material temperature and a max. 0.36% increase in material relative humidity. Another important aspect was looking at the water content of the entire building envelope in each climate zone. We found that the building envelope containing salt shows a greater average water content of up to 13.0% in cold climate zones and lower average water content in warmer climate zones. The same influence of cold or warm climate zones on water content in the thermal envelope can reasonably be supported by the studies of Qin et al. [82] Liu et al. [83], Corrado et al. [84] and Qin et al. [85]. The highest risk of salt deliquescence is observed in TR and ME climate zones, with the lowest risk in the AR zone.

Due to the limitation of the in situ measurements, only the T and RH near the indoor and outdoor surfaces of the tested materials are measured. The simulated results show good agreement with in situ measurements for salt and gypsum in the CO zone. Both results show the same tendency in values of material temperature and humidity. However, the measured temperature at the indoor surface is slightly higher and the RH slightly lower than the simulated ones, probably due to the tested materials being located near the central heating element from Sept 26, 2019 till Dec 18, 2019. Previous studies by Moujalled et al. [86] and Illomets et al. [87] have also found that in situ measurements show slightly different results as simulations due to the heating system. However, the modelling method is shown to be correct, but will have to be adapted to real living conditions such as building envelope, occupation (behaviour and density), and energy system in the future.

The annual simulation for energy consumption in WUFI®Plus shows that salt has a slightly increased heat and decreased moisture transport, which leads to more cooling, heating, and dehumidification energy. However, salt has advantages in increased heat transport that reduce the indoor surface temperature, the peak of indoor air temperature, and is moreover beneficial for better indoor comfort in very hot climate zones. Decreased moisture transport in salt shows it can help to reduce the influence of the external environment RH with respect to indoor RH or it can prevent the condensed water and indoor moisture from drying out. This result correlates with other works in which the hygrothermal performance of materials in the building envelope have been studied [1,3,61,87].

The outcomes mentioned above can form the basis for some recommendations on the application of salt in internal spaces. In general, for buildings without HVAC only very dry and hot outdoor climatic environments (AR zone) are suitable as there is no risk of salt deliquescence, while the salt has a positive influence on the Ti/RHi and durability of the thermal envelope. For buildings with good thermal envelopes and controlled HVAC, the CO, TE, and SP zones might also come into consideration.

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## A-3: Paper: Reuse of salt waste in 3D printing: Case study

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# *Reuse of salt waste in 3D printing: Case study*

*Salt waste, Printing mortar, Printability,*
*Case Study, 3D printing*

**Summary**

Salt waste from desalination plants and potash mining industry already presents an environmental problem. Salt (NaCl) in combination with other materials shows promising mechanical and physical properties and has already been used as a building material in the past.
This experimental study focuses on using salt in 3D printing technology to improve the resource efficiency of both the building material and construction process (speed, cost, accessibility).
To analyze the printability of salt mortars, four different material groups (SS- salt and starch, SC – salt and clay, CS – salt and concrete, SG – salt and gypsum) each prepared in six different mixes were evaluated according to a range requirements (pumpability, printed shape maintenance before it hardens, proper binding time around 30 minutes, possibility to build another layer and surfaces).
The most promising printing mortar was selected for a 3D printing process with a clay printer (Potter Bot Micro 10) for more complex print objects.
The SC printing mortar performed the best in terms of printability requirements, stayed stable after the hardening period and also preserved the complex printing shape. However, SC print objects showed high efflorescence on the surface and connection problems between printing layers on some positions.
In the future special attention should be given to the further development of the printing mortars. In general, experimental results demonstrate that salt printing mortars provide a promising method for 3D printing.

## Introduction

The world population and with it, the use of natural resources are growing. Water shortages affect around 3.6 billion people [United Nations Secretariat, 2002]. One solution to this water shortage is to desalinate seawater. Around 16,000 desalination plants are already working around the world that extract fresh water from seawater and discharge 142 million cubic metres of hypersaline brine (ca. 8,45 million m3 salt a day)  into the sea [Jones, Qadir, van Vliet, Smakhtin, & Kang, 2019].

The United Arab Emirates alone are responsible for the production around 120 million tons of salt per year. Another huge amount of salt waste (NaCl) is created in potash production [Rauche, 2015]. Potash is used as a fertilizer in extensive agriculture and the byproduct of its production (mostly salt) is disposed into nature (Figure 1). The negative environmental impacts due to the increased salt content in the seas, rivers and earth have been already acknowledged in literature [Hoepner & Lattemann, 2003; Musfique & Rifat, 2012; Palomar & J. Losada, 2011].

The use of salt in building construction is usually associated with possible damage rather than in relation to its value. Salt (NaCl) is porous at room temperature, dissolves in water and stores thermal energy and moisture [Bauer, Song, & Sanborn, 2019; Feldman, 2003; Ferguson, 1922; Gevantman, 1981; Sayem Zafar, 2015]. Moreover, salt caves and salt rooms are acknowledged as a therapy against sleep disorders, depression and respiratory diseases. In the past salt was used in combination with other materials (clay, concrete, starch) as a building material, or was cut and used in block from nearby salt seas or underground mines [Petruccioli & Montalbano, 2011; Rovero, Tonietti, Fratini, & Rescic, 2009].

Since a direct application of salt waste is not possible (salt is too porous), combinations with binders and new technological processes such as 3D printing (additive manufacturing) shows further potential.

3D printing is a technology that allows for a higher complexity of design, more automatization and lower production costs in the construction of one-offs and small series [Blok, Longana, Yu, & Woods, 2018; Zhang, Wang, Dong, Yu, & Han, 2019]. Various technical processes such as binder jetting [Gonzalez, Mireles, Lin, & Wicker, 2016] and paste extrusion [Patel, Blackburn, & Wilson, 2017], have already been described in the literature on 3D-printing with salt [Ganter, 2011; Geboers, 2015; Rael & San Fratello, 2018; Yuan, Ding, & Wen, 2019]. However, only two salt mixtures have been used and documented in the literature on 3D printing [Ganter, 2011; Rael & San Fratello, 2018].
Therefore, in an attempt to use salt waste to increase the resource efficiency of the building materials and optimize the constructional flow (cost, time), other mixes for salt (NaCl) mortars in 3D printing technology were investigated and carried out at the Chair of Building Construction and Material Science EBB, TUM.

*Figure 1. Potash tailings stack Kali monutain at Heringen, Germany [Photo: Vesna Pungercar].*

## Methods and materials

This experimental research was motivated by increasing trends to use waste materials in building construction. The methodology analyses the potential and limitation of salt materials used as printing mortars in the 3D printing. The main part of the investigation was to identify potential binders in literature, to define the mixing ratio of salt (rock salt) and binder for printing and to reveal the most appropriate salt mortar for printing (Figure 2).

Different salt mixtures were first injected by hand onto a Plexiglas plate in a circular form of up to three layers, hardened at room temperature and evaluated after one to three days. These first prototypes were used to study the mixing ratio of salt and binder and the quality of the printed objects were studied (pumpability, printed shape maintenance, proper binding time, possibility to build up another layer and surface smoothness). The most promising mixture was selected for 3D printing with a clay printer (Potter Bot Micro 10) to print more complex designs.

The materials used during the study were: salt (NaCl), sand (0,1-0,4mm grain), cement, gypsum (hemihydrate), water, starch (Maltodextrin), clay and water. They were listed in the Table 1 to show dif-

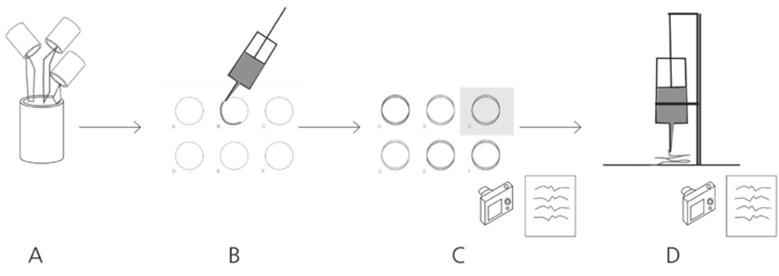



*Figure 2. Method for the experimental study.A - mixing materials, B – experimental printing with hand injection, C – selection of the most appropriate printing salt mortal, D – printing the selected mortal with 3D-print [Original from authors].*

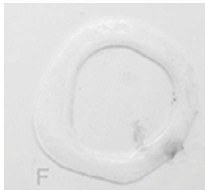
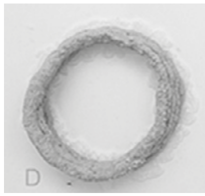
ferences between mortars. The material mixtures were divided into 4 different groups and named after composition of salt and binder: SS (salt and starch), SC (salt and clay), CS (salt and concrete) and SG (salt and gypsum).
Each material group had six mixes (recipes from A to F) with different mixing ratio of salt, binder and water. Recipe A in 4 groups was always the initial mix based on the literature review. The following recipes (B-F) were continuously adjusted due to observation of the previous recipe. For example: the recipe A of mortar SC was too liquid, so in the recipe B the water amount was decreased. Resource efficiency of each mortar was shown with the salt and binder ratios.

## Results and discussion

It was observed that the binders significantly changed the properties of porous salt. The presence of starch (SS) greatly increased the viscosity of the mortar so that it became impossible to create the shape. The main disadvantages in the SG group were their short binding and hardening times. Materials from the CS group were not plastic enough and took too long to dry.
The SC group was very easy to pump; the shape of the printing prototype was easily maintained; binding time was short; and it was easy to build another layer. However, the surface of fresh or hardened mortar changed as it hardened and high levels of efflorescence occurred on the surface.
Quality of the mortars was measured with printability requirements and a basic scale of 1 to 3. The scale 1 represents a maximum score with a good performance, 2 a middle score with an average performance and 3 a minimum score with a bad performance (Table 2). The mortar with the highest number of the scale 1 is the best-evaluated mortar. At the end of this investigation, the printing salt mortar from group SC (recipe D) was selected for more complex 3D printing with the clay printer.

| Group | Recipe | Ratio salt/binder | Salt [g] | Clay [g] | Fresh water [g] | Sand [g] | Cement [g] | Gypsum [g] | Starch [g] |
|---|---|---|---|---|---|---|---|---|---|
| SS | A | **88:12** | **352** | - | **10** | - | - | - | **48** |
| | B | 50:50 | 200 | - | 100 | - | - | - | 200 |
| | C | 61,5:38,5 | 200 | - | 40 | - | - | - | 125 |
| | D | 21:79 | 80 | - | 40 | - | - | - | 300 |
| | E | 46:54 | 90 | - | 40 | - | - | - | 105 |
| | F | 30:70 | 45 | - | 40 | - | - | - | 105 |
| SC | A | 70:30 | 280 | **120** | 100 | - | - | - | - |
| | B | 70:30 | 280 | **120** | 60 | - | - | - | - |
| | C | 80:20 | 320 | **80** | 60 | - | - | - | - |
| | D | 60:40 | 240 | **160** | 60 | - | - | - | - |
| | E | 65:35 | 260 | **140** | 40 | - | - | - | - |
| | F | 65:35 | 260 | **140** | 60 | - | - | - | - |
| CS | A | 50:50 | 600 | - | 320 | **480** | **230** | - | - |
| | B | 60:40 | 480 | - | 190 | **576** | **144** | - | |
| | C | 60:40 | 480 | - | 190 | **576** | **144** | - | - |
| | D | 60:40 | 320 | - | 104 | **384** | **96** | - | - |
| | E | 70:30 | 240 | - | 104 | **448** | **112** | - | - |
| | F | 80:20 | 160 | - | 104 | **512** | **128** | - | - |
| SG | A | 50:50 | 50 | - | 20 | - | - | **50** | - |
| | B | 60:40 | 60 | - | 15 | - | - | **40** | - |
| | C | 60:40 | 60 | - | 18 | - | - | **40** | - |
| | D | 50:50 | 50 | - | 18 | - | - | **50** | - |
| | E | 70:30 | 70 | - | 16 | - | - | **30** | - |
| | F | 40:60 | 40 | - | 19 | - | - | **60** | - |

*Table 1. Mortar printing mixtures [Original from authors].*

| Group | Recipe | Pumpability | Printed shape maintenance | Proper binding time | Possibility to build another layer | Surfaces | Photo of the best mix |
|---|---|---|---|---|---|---|---|
| SS | A | 3 | 3 | 3 | 3 | 1 |  |
| | B | 3 | 3 | 3 | 3 | 1 | |
| | C | 3 | 3 | 3 | 3 | 1 | |
| | D | 2 | 3 | 3 | 3 | 1 | |
| | E | 2 | 2 | 3 | 3 | 1 | |
| | F | 2 | 2 | 2 | 3 | 1 | |
| SC | A | 2 | 3 | 2 | 3 | 2 |  |
| | B | 1 | 2 | 1 | 1 | 1 | |
| | C | 2 | 1 | 1 | 1 | 2 | |
| | D | 1 | 1 | 1 | 1 | 1 | |
| | E | 3 | 3 | 1 | 3 | 3 | |
| | F | 1 | 2 | 1 | 2 | 2 | |
| CS | A | 1 | 2 | 3 | 3 | 2 |  |
| | B | 2 | 3 | 3 | 3 | 3 | |
| | C | 2 | 3 | 3 | 3 | 2 | |
| | D | 2 | 2 | 3 | 3 | 2 | |
| | E | 1 | 2 | 2 | 3 | 2 | |
| | F | 1 | 2 | 2 | 2 | 1 | |
| SG | A | 3 | 3 | 3 | 3 | 3 |  |
| | B | 3 | 3 | 2 | 3 | 3 | |
| | C | 2 | 3 | 3 | 3 | 3 | |
| | D | 3 | 3 | 3 | 3 | 3 | |
| | E | 3 | 3 | 3 | 3 | 3 | |
| | F | 1 | 2 | 3 | 2 | 2 | |

*Legend: 1 -good, 2-average, 3-bad*

*Table 1. Printability requirements for mortars [Original from authors].*

The SC mortar also resulted in good printed quality of complex prototype objects using the clay printer.
Most of the time, it was possible to press fresh SC mortar through a 5mm nozzle while preserving the printing shape.
However, in some cases, the high porosity of the printing mortar decreased its fluidity, causing a slower flow and the poorer connection of the printed layers.
After the hardening period, the prototypes did not shrink significantly but stayed stable.

## Conclusion

This paper focuses for the first time on using salt waste as a component of building materials for 3D-printing technology.

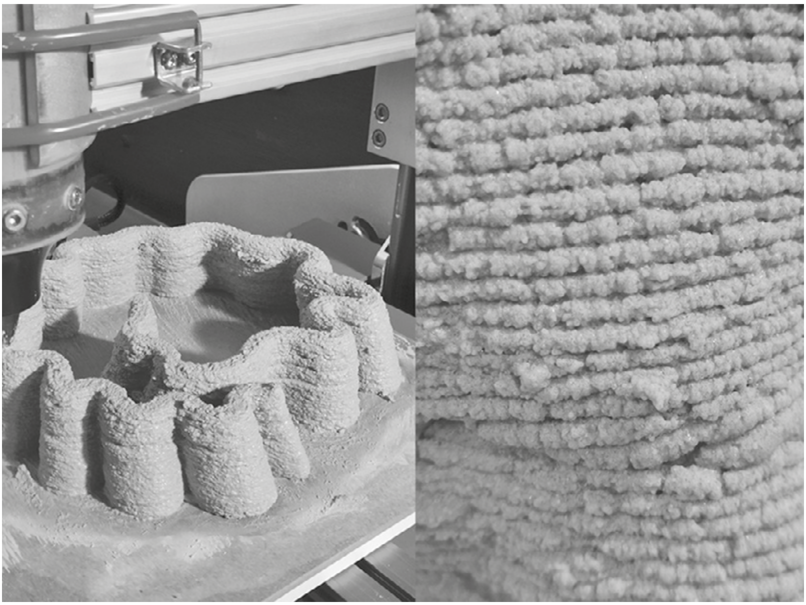


*Figure 3. 3D print prototype with SC(left). Connection of printed layers of SC mortar (right) [Original from authors].*

Results shows that salt with clay best met printability requirements of all printing mortars. However, other salt printing mortars should be further investigated with other additives (superplasticizer, restrainer or viscosity modifier) and 3D printers.
We believe that using salt with 3D-printing technology increases the resource and building process efficiency and will acquire further significance in the field of building construction.

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## A-4: Paper: 3D print with salt

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# 3D Print with Salt

**Vesna Pungercar, Martino Hutz, and Florian Musso**

**Abstract** Sustainable materials and additive manufacturing have the potential to increase material efficiency and minimize waste in the building process. One of the most promising materials is salt (sodium chloride). It is highly available as a residue of desalination and potash production processes and attracts attention due to its material properties (storage of humidity and heat). This research presents an investigation and evaluation of using salt as an alternative material in additive manufacturing. Thus, the focus of the study was on small-scale 3D printing with paste extrusion. Experimental studies of different salt mixtures with different binders, printing properties and other parameters were analyzed in three stages. In the first phase (P1) the mixing ratio of salt and potential binders (clay, gypsum, cement and starch) was defined; in the phase two (P2) the most promising mixture was selected, modified by additives and investigated by 3D image scan measurements; and in the last third phase (P3) the potential applications of salt in additive manufacturing were presented. As the research shows, the salt in material extrusion processes can substitute the main material by up to 70%, is successfully manipulated with different additives (to improve the workability of the printing mortar) and is highly dependent on the printer‘s settings. For future full-scale 3D printing with salt many steps still have to be taken. However, incorporating salt in additive manufacturing showed a potential of saving material resources, addressing environmental issues and initiating new construction processes.

**Keywords** Salt · Additive manufacturing · Experimental studies · Potentials · Sustainability of materials

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# 1 Introduction

Building materials are of great importance for our society and are used to protect us from the outdoor weather conditions and to influence our physical/psychological well-being [1–3]. However, meeting world material needs is becoming more difficult each year due to the growth of the world population [4], increasing climatic changes [5] and restricted commercial activities such as the COVID-19 disease [6]. The construction sector is, in Europe, not only responsible for 50% of overall material consumption but also for the generation of one third of the total waste and 5–12% of total European greenhouse emissions [7]. So finding more available, affordable and environment friendly materials and using more efficient technological processes such as 3D printing will help to save material resources and minimize the impact of the whole building process [8–10].

## *1.1 Salt as a Resource*

One of the new promising materials is salt (sodium chloride), which has been a valuable material for many centuries. During the past decades it has attracted wide attention as a residue of desalination and potash production. Due to increasing demand for fresh water and its limited supply, almost 47% of the world population does not have enough fresh water for at least one month each year [11]. In some coastal areas seawater has been used as a resource for producing fresh water. The process of extracting fresh water from seawater and discharging the residue (hypersaline brine) into the sea is called desalination. Around the world, some 15,906 operational desalination plants (see Fig. 1) produce a total of 95 million cubic metres of desalinated water per day and an estimated 142 million cubic metres of hypersaline brine, of which approximately 8.45 million cubic metres of salt per day are disposed into the sea [12]. In terms of its origin, 70.3% of global brine disposal comes from the Middle East and North Africa, 10.5% from East Asia and Pacific, 5.9% from Western Europe, 3.9% from North America, 3.9% from Latin America and Caribbean, 2.6% from Southern Asia, 1.8% from Eastern Europe and Central Asia and 1.0% from Sub-Saharan Africa. The disposal of hypersaline brine into the sea and its negative

**Fig. 1** Desalination plant in RAK (Ras Al Khaimah, United Arab Emirates). Licensed under the Creative Commons Attribution 2.0 Generic license. *Source* Wikimedia Commons [17]

environmental consequences have already been acknowledged in scientific research. The observed negative effects include; change of water quality (increase of salinity, temperature), less light passing through the water (due to the growth of algae), and a reduction of biodiversity (fish, corals) [13–15]. At the moment there is a lack of regulation for brine disposal into nature, although measures such as brine discharge system configurations or the reuse of the brine are proposed in different research projects [14, 16].

Another source of salt waste (NaCl) is the potash industry [18]. Due to extensive agriculture, many fertilizers are used to enhance crop growth. One common fertilizer is potash as found in sylvite and carnalite minerals [18]. The remainder of the minerals consists of salt (NaCl) and small amounts of clay, silt, sand, and dolomite [19]. Taking into account that annual global production presents around 68.1 million tons of potash [20], salt waste (83.5 wt% of the mineral) can be calculated at around 335 million tons a year. Salt waste from mining (see Fig. 2) is also disposed into nature as salt tailing on the surface [18], as brine injection/backfilling underground or as direct discharge to rivers and seas [21]. One of the best known salt tailings in Germany is the roughly 250 m high "Monte Kali" composed of 236 million tons of mining salt waste [22]. It has been discovered that the salt contamination to nearby waters are clearly caused by the salt load and prevents "a permanent recolonization by typical sensitive freshwater species" [23]. In Spain and Canada researchers discovered various negative environmental effects caused by potash mining activities: a decrease of water conductivity and the number of living communities in the Llobregat Basin [24] and a devastating impact of high salt concentration in the rivers near Saskatchewan's potash mines [19]. If the world's annual salt waste were spread on the surface of the city of Munich (310.43 $m^2$) a 54 m-high layer of salt would be created within 5 years.

**Fig. 2** Potash tailings stack Monte Kali, Heringen, Germany. *Photo*: Vesna Pungercar, 2020

## 1.2 Salt Properties

Sodium chloride or table salt is one of the best-known substances on the Earth. It consists of two different elements: Na (Sodium) and Cl (Chloride), which are linked by an ionic bond [25, 26]. Salt crystals come in different sizes, are white and without smell [27]. Microscopically observed, salt does not have many open spaces in its structure and is known for its low permeability and porosity [28]. Literature records sodium chloride's specific heat as between 0.853 J/(gK) [29] and 0.859 J/(gK) [30, 31]. The thermal conductivity of salt varies from 6 to 6.5 WmK at room temperature [29, 32–35] and 3.3 W/mK at higher temperatures (approx. 300 °C) [35]. Salt melts at 801 °C [36, 37] and is used for heat storage in solar power plants [37].

In addition to the properties noted above, salt can dissolve in water, methanol or formic acid [29]. At a relative humidity above 75.3% [29] salt crystals start to dissolve and change to brine (salt with water). However, in the drying process the water evaporates and crystals start to grow again. During the past decades, salt rooms have been developed and used for drug free treatment of respiratory illness, skin diseases [38] and lung cancer cells [39]. The treatment consists of sitting in salt rooms, salt caves or at the seaside and breathing air saturated with salt particles (aerosols) [40, 41]. Several studies focus on the positive effect of treatment with a saline environment [39, 41–43], but unfortunately no research has been conducted about how salt as construction material impacts the quantity of aerosols in indoor environments and health.

## 1.3 Salt Materials in Building Construction

In historic building construction, salt materials were mostly used in dry-hot weather conditions and in locations where conventional resources were not available. In some cases, salt materials were cut from nearby salt seas or mines and used directly as a building block for exterior walls [44–46]. One of these buildings is the hotel "Palacio de Sal" in Salar de Uyuni in Bolivia (Material District 2016), which is built out of about a million salt blocks. Other salt-based construction materials are mixtures of salt and different binders (clay, volcanic ash, cement or starch) [44, 47].

Karshif and Roman maritime materials are among the oldest existing mixed salt materials. Karshif, from the Siwa Oasis in Egypt, is a material for load bearing walls made of small salt rocks (up to 95% of the material) and salt-clay mortar [44]. Due to its hygrothermal and chemical properties, Karshif stone can be formed to "a sort of monolith" [48] under repeated cycles of absorbing humidity from the environment and emitting it again. The Romans mixed volcanic ash, lime and seawater [49] to build highly durable protection walls in the Mediterranean sea. Different studies on the long-term compressive strength of concrete made with seawater discovered that there is almost no difference to that of concrete mixed with freshwater [50–52]. Other mixtures of concrete and salt were developed for the protection of radioactive waste in abandoned salt caves [53–57], here salt comprised around 50% of the whole mass [53].

Further salt materials may be produced by pressing, melting, additive technology or natural salt crystallization. Salt lick blocks [58] are made of compressed salt as an additive to animal nutrition and dissolve with animal saliva [59–62] if they do not contain special additives [63] or coatings [62]. Salt crystallization processes are used in contemporary art and architectural structures by soaking different materials in very salty water or leaving materials outside to dry. Over time, salt crystals grow and create salt crusts which are also used as artworks or as shading systems [64–67].

New salt mixtures (salt and starch) have gained attention in the last decades as a result of a recent building technology made possible by advances in data processing—additive manufacturing [68–70] (see Fig. 3). The first 3D printing prototypes were developed by a research team at the Solheim Additive Manufacturing Laboratory of the Mechanical Engineering Department of the University of Washington [68, 69] (see Fig. 3). Their 3D printed elements were composed of salt (8 parts by weight), maltodextrin (1 part by weight) and water. The same recipe was later adapted and slightly modified by researchers from Emerging Objects to create a 3D-printed salt pavilion [71] (see Fig. 3) and by TU Delft to examine mechanical properties of the salt-starch mixture [69]. Researchers from Japan mixed salt-starch with wheat flour and dextrin to create 3D moulds [72].

**Fig. 3** Left—additive manufacturing. Right above—the first 3D printing salt prototypes. Right below—the 3D-printed salt part for a 3D-printed salt pavilion. *Source* Left—TUM EBB. Right above—The Solheim Additive Manufacturing Laboratory of the Mechanical Engineering Department of the University of Washington [68, 69]. Right below—Emerging Objects/Ronald Rael and Virginia San Fratello [71]

## 1.4 3D Printing with Salt

As a porous material salt has a potential in additive manufacturing processes if it can be bound. There are various methods in additive manufacturing such as binder jetting, fused deposition modelling and paste extrusion. However, the most common processes that have been used with salt are binder jetting [68, 69, 71, 72] and paste extrusion. Binder jetting was invented almost 30 years ago at the Massachusetts Institute of Technology [69] and generally includes spreading a thin layer of powder, deposing a binder on the powder, repeating the first two steps multiple times and if needed applying a heat treatment [73]. Paste extrusion includes mixing solids with a liquid binder, pushing the paste through a nozzle, thus creating an object layer by layer from the bottom up [74] (Fig. 4).

Dr. Mark Ganter and his team from University of Washington [69] were the first to use binder jetting for salt and succeeded in creating the first, very small 3D printed objects (up to 5.2 cm). Only some years later a research team from "Emerging Objects" used the same 3D printing process and powder mixtures (salt and maltodextrin) but a different binder (rice wine). They developed 3D printed salt elements which were light, translucent and waterproof due to a coating with wax. 330 salt printed elements were connected to create a salt pavilion called Saltygloo [71]. This recipe was also used by a student from UC Berkeley to print his 3D master-thesis model [75].

Paste extrusion processes with salt were examined by the researcher and designer Karlijn Sibbel who managed to print small 3D printed salt objects with a low height (less than 10 cm) and a low quality [76]. Unfortunately, we were unable to find any scientifically relevant information about the mixtures and the process. Japanese [72] and Swiss researchers [77] have been investigating the creation of salt scaffolds by paste extrusion which can later be removed by soaking the object in water (salt leaching).

Most previous research in this area has focused on salt materials' properties themselves rather than whether the salt materials are appropriate for 3D printing and which additive manufacturing process is the most appropriate for salt. As a consequence

**Fig. 4** Left and right—a 3D-printed salt pavilion. *Source* Emerging Objects/Ronald Rael and Virginia San Fratello [71]

of the increase of building with 3D printing devices on construction sites, a better understanding of the interaction between 3D printing materials and additive manufacturing is growing. Nevertheless, the challenge of using more resource efficient materials in 3D printing persists. In this paper, we address these research gaps by using salt waste as a means to improve the resource efficiency of printing materials and to evaluate advantages and disadvantages of using it in paste extrusion processes.

## 2 Experimental Studies

The main objective of our three experimental studies is to create and evaluate salt mixtures in small-scale material extrusion processes and collect information for future research with large-scale 3D printing. All 3D printing experiments were conducted with a clay printer called “Potter Bot Micro 10” at the “Low-Cost-Lab” of the Chair for Design, Construction and Materials (EBB) at the architectural faculty of the Technical University of Munich.

The goal of our study was to evaluate all parameters that influence the quality of printed objects. These parameters are: printer properties (printing speed, extrusion flow rate, nozzle size), material properties (mixing ratio, water content, type of binder, other components) and other modelling or thermodynamic processes (heating the mortar, drying 3D printed objects in the oven).

The literature reveals various methods for evaluating the quality of printed objects [78–80]. We analysed the printed salt objects in three stages using different methods. In the first phase (P1) the mixing ratio of salt and potential binders (clay, gypsum, cement and starch) was defined by continuously improving the quality of the printed objects [81] and evaluating it with printability criteria found in literature [82]. In phase two (P2) the most promising mixture was selected and further modified by using different additives. Then the mixtures were analysed by 3D scan and image measurement methods [79]. In the third phase (P3) potential applications of salt mixtures in 3D extrusion processes were analysed and printed at small-scale. The materials used in these studies were salt, clay, Portland cement, silica sand, starch (maltodextrin), water and gypsum, their properties are listed in Table 1.

### *2.1 Experimental Study 1: Salt/Binder*

#### 2.1.1 Material

In this experimental study, the advantages and disadvantages of salt materials in paste extrusion processes were analysed. After identifying potential binders in literature, we investigated the mixing ratio of salt and binder. Again, the materials used are listed in Table 1.

**Table 1** Materials used in the all phases

| Material | Producer | Product properties |
|---|---|---|
| Salt (NaCl) | Diacleanshop | White colour, pharma quality, Eur. Ph, USP, MG 58.44 g/mol, grain: 1 mm |
| Clay | Sibelco | WM2505, white colour, Firing temperature: 1000–1300 °C Firing color: light cream–light grey, grain: 25% with 0–0.2 mm grain size |
| Portland cement | Solnhofer Portland Zementwerk GmbH | Normal cement CEM I 42.5 N, normal early strength, normal post-hardening, normal hydration heat development |
| Silica sand | Sika | Grain: 0.063–0.3 mm |
| Natural gypsum | Diacleanshop | Calcium sulfate dehydrate, powder |
| Starch (Maltodextrin) | Myprotein | 100% maltodextrin carbs, powder |
| Alcohol (Isopropyl) | spinnrad | 2-Prapanol, 99.5% |

Four typical salt mixtures were named according to the composition of salt and binder: SS (salt and starch), SC (salt and clay), CS (salt and concrete) and SG (salt and gypsum) [81]. The SS mixture is a the most frequently used salt mixture in binder jetting process [68, 69, 71, 81]. The SC mixture is still unknown in 3D printing. However, it has existed as a traditional material for 2600 years in the Siwa Oasis, Egypt [44]. CS is based on a mixture common in concrete construction (Portland cement, silica sand and water) without any additives (bentonite or superplastificier). The SG mixture consists of gypsum, salt and water and its main challenge was expected to be the speed of the drying process.

### 2.1.2 Methodology

The mixing ratio of salt and binders was defined by experiments in which the salt mixtures were continuously improved [81] and at the same time evaluated with visual printability criteria such as pumpability, printed shape consistency, proper binding time, acceptance for building up another layer and smoothness of the surface [82]. The first prototypes were mixed in a pot (A) and experimentally printed by hand injection onto a transparent Plexiglas plate (B) in a circular form of up to three layers, hardened at indoor room temperature and evaluated after one to three days (C) (Fig. 5).

Table 2 shows the four salt groups (SS, SC, CS, SG) with 6 mixes each (recipes from A to F), exploring the application in additive manufacturing. The initial mix of each group is always Recipe A. The following mixes (B–F) were continuously modified following the investigation and evaluation of the previous mix. For example,

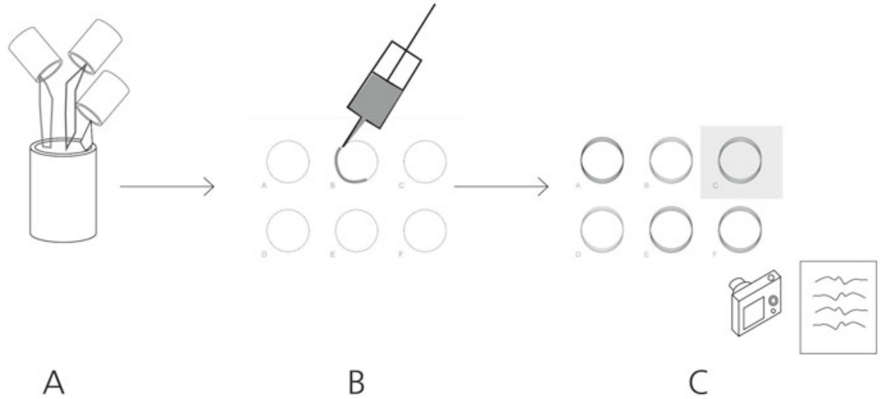



**Fig. 5** Method for the experimental study. A—mixing materials, B—experimental printing with hand injection, C—hardening at indoor room temperature and evaluating after one to three days. Image: Vesna Pungercar [81]

if the printing mortar in recipe A was too liquid or too dry, the amount of water was decreased or increased in recipe B. In the event that the mortar in recipe B had appropriate printability, in recipe C the amount of salt was increased to gain higher resource efficiency. The resource efficiency increased with a higher amount of salt in the mixture.

### 2.1.3 Results

All salt mixtures were evaluated on a basic scale of 1 to 3 according to their poor, median or good printing qualities. 1 represents a maximum score (good performance), 2 a middle score (average performance) and 3 a minimum score (bad performance) (Table 2). The mortar with the highest number of scale 1 grades was considered to be the best mortar and was further examined with our 3D printer (bold in Table 3).

We observed that the conventional and traditional materials (concrete, clay, gypsum, starch) always failed to contribute to an adequate printing mortar when used together with salt in the initial mix. Thus further adjustments depending on the binder were made so that the printing mortar could pass through the nozzle of the hand injection device and stay stable in the 3D object (cylinder).

The SS (salt and starch) mixture had white colour and no odour or salty taste. As described in literature the starch was mixed in warm water to create a substance similar to gelatine and was subsequently mixed with salt. However, the resulting mortar was impossible to print. At the beginning, the mixture was too hard and after decreasing the amount of salt, too fluid. We noticed that the starch increased the viscosity of the mortar so much that at the end all printed layers connected to a circular form of up to three layers and did not stay stable. After drying, the printed object had a translucent, shining and hard surface.

**Table 2** The recipes of salt mixtures. *Source* Authors [81]

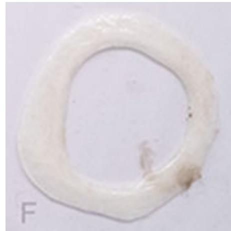
| Group | Recipe | Ratio salt: binder | Salt (g) | Clay (g) | Fresh water (g) | Sand (g) | Cement (g) | Gypsum (g) | Starch (g) |
|---|---|---|---|---|---|---|---|---|---|
| SS | A | 88:12 | 352 | – | 10 | – | – | – | 48 |
| | B | 50:50 | 200 | – | 100 | – | – | – | 200 |
| | C | 61.5:38.5 | 200 | – | 40 | – | – | – | 125 |
| | D | 21:79 | 80 | – | 40 | – | – | – | 300 |
| | E | 46:54 | 90 | – | 40 | – | – | – | 105 |
| | **F** | **30:70** | **45** | – | **40** | – | – | – | **105** |
| SC | A | 70:30 | 280 | 120 | 100 | – | – | – | – |
| | B | 70:30 | 280 | 120 | 60 | – | – | – | – |
| | C | 80:20 | 320 | 80 | 60 | – | – | – | – |
| | **D** | **60:40** | **240** | **160** | **60** | – | – | – | – |
| | E | 65:35 | 260 | 140 | 40 | – | – | – | – |
| | F | 65:35 | 260 | 140 | 60 | – | – | – | – |
| CS | A | 50:50 | 600 | – | 210 | 480 | 120 | – | – |
| | B | 60:40 | 480 | – | 190 | 576 | 144 | – | – |
| | C | 60:40 | 480 | – | 190 | 576 | 144 | – | – |
| | D | 60:40 | 320 | – | 104 | 384 | 96 | – | – |
| | E | 70:30 | 240 | – | 104 | 448 | 112 | – | – |
| | **F** | **80:20** | **160** | – | **104** | **512** | **128** | – | – |
| SG | A | 50:50 | 50 | – | 20 | – | – | 50 | – |
| | B | 60:40 | 60 | – | 15 | – | – | 40 | – |
| | C | 60:40 | 60 | – | 18 | – | – | 40 | – |

(continued)

**Table 2** (continued)

| Group | Recipe | Ratio salt: binder | Salt (g) | Clay (g) | Fresh water (g) | Sand (g) | Cement (g) | Gypsum (g) | Starch (g) |
|---|---|---|---|---|---|---|---|---|---|
| | D | 50:50 | 50 | – | 18 | – | – | 50 | – |
| | E | 70:30 | 70 | – | 16 | – | – | 30 | – |
| | **F** | **40:60** | **40** | – | **19** | – | – | **60** | – |

**Table 3** Printability evaluation for salt mixtures. Photos: Martino Hutz [81]

| Name | Recipe | Pumpability | Printed shape maintenance | Proper binding time | Possibility to build another layer | Surfaces | Photo of the best mix |
|---|---|---|---|---|---|---|---|
| SS | A | 3 | 3 | 3 | 3 | 1 |  |
| | B | 3 | 3 | 3 | 3 | 1 | |
| | C | 3 | 3 | 3 | 3 | 1 | |
| | D | 2 | 3 | 3 | 3 | 1 | |
| | E | 2 | 2 | 3 | 3 | 1 | |
| | F | 2 | 2 | 2 | 3 | 1 | |
| SC | A | 2 | 3 | 2 | 3 | 2 |  |
| | B | 1 | 2 | 1 | 1 | 1 | |
| | C | 2 | 1 | 1 | 1 | 2 | |
| | D | 1 | 1 | 1 | 1 | 1 | |
| | E | 3 | 3 | 1 | 3 | 3 | |
| | F | 1 | 2 | 1 | 2 | 2 | |

(continued)

**Table 3** (continued)

| Name | Recipe | Pumpability | Printed shape maintenance | Proper binding time | Possibility to build another layer | Surfaces | Photo of the best mix |
|---|---|---|---|---|---|---|---|
| CS | A | 1 | 2 | 3 | 3 | 2 |  |
| | B | 2 | 3 | 3 | 3 | 3 | |
| | C | 2 | 3 | 3 | 3 | 2 | |
| | D | 2 | 2 | 3 | 3 | 2 | |
| | E | 1 | 2 | 2 | 3 | 2 | |
| | F | 1 | 2 | 2 | 2 | 1 | |
| SG | A | 3 | 3 | 3 | 3 | 3 |  |
| | B | 3 | 3 | 2 | 3 | 3 | |
| | C | 2 | 3 | 3 | 3 | 3 | |
| | D | 3 | 3 | 3 | 3 | 3 | |
| | E | 3 | 3 | 3 | 3 | 3 | |
| | F | 1 | 2 | 3 | 2 | 2 | |

The SC (salt and clay) mixture: had brown colour, a light odour and a taste of soil. Clay, salt and cold water were mixed in a pot. The initial mixture was too fluid, so the amounts of water and saltin the further recipes (B–D) were decreased. Although recipe D had the best printability and workability, the amount of salt was experimentally decreased in the next steps. More salt increased the porosity of the material and influenced the application of the printing mortar negatively. Therefore, recipe D was chosen as the best printing mortar of all clay-salt studies. Its advantages were easy pumpability, keeping the shape and a short binding time (Fig. 6).

The CS (salt and concrete) mixture: had a dark grey colour, a strong odour and a taste of cement. The CS mixture contained at first a mix of cement, sand and salt. Afterwards cold water was added. None of the six of recipes were useable. To push the material through the nozzle the mixture had to be fluid, otherwise it was impossible to print. We suspect that the aggregate content (sand, salt) was too high and congested the injection nozzle. After hand-printing it remained unstable, was not plastic enough and took too long to dry.

The SG (salt and gypsum) mixture had a light brown-grey colour, a faint odour and a taste of gypsum. Gypsum, salt and cold water were mixed in a pot. The initial mixture could be pushed through the nozzle although the stability of the printed object was not perfect. In the recipes from B to E an attempt was made to decrease the water and gypsum content. However, either the mix would not pass through the hand injection device or it was too fluid. At the end the amount of salt was decreased


**Fig. 6** (clockwise from top left) Material mixtures, Salt and Starch, Salt and Clay, Salt and Gypsum, Salt and Concrete. *Photos* Martino Hutz

and the mortar became useable for printing (recipe F). Although the modified mixture performed more favourably than the others, its binding and hardening times were too short.

The best mixture of all salt mortars was salt and clay (SC, recipe D) and was thus further analysed in phase two.

## 2.2 *Experimental Study Two: Salt Cylinder*

### 2.2.1 Material

The most promising salt-clay mixtures from experimental study one (P1) were further analysed and refined in this second study (P2). The goal was to investigate the influence of salt and additives on the printing quality of 3D printed cylinders. Different additives were used to improve the surface quality and change the viscosity (starch) as well as structural stability (straw) for potential applications. As the salt-starch-mixtures from the experimental study one did not show positive printing properties, the objective was to further investigate starch-salt-clay mixtures. To influence viscosity and gain control over the efflorescence, starch with alcohol (Table 1) was added to the salt-clay mixtures: Alcohol lowers the solubility of starch by attracting water and prevents the formulation of non-Newtonian fluids (only starch and water). To improve the overall stability in the salt-mixtures a natural reinforcement material was tested. Since the 3D printing process and traditional steel reinforcement are not very compatible, fine fibres were added to the material mixture similar to GFRC (fibre reinforced concrete). Straw was selected for its widespread availability and positive thermal potential.

Cylinders of four different materials were 3D printed for comparison: C (clay), CS (salt-clay), CSS (salt-clay-straw) and SSC (salt-starch-clay) (see Fig. 7).

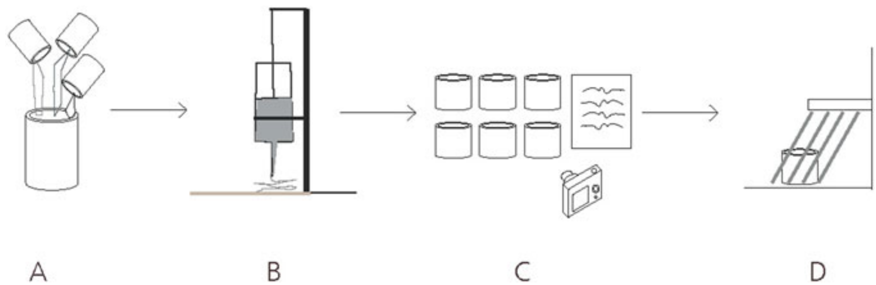



**Fig. 7** Method for the experimental study two. A—mixing materials, B—3D printing, C—hardening at indoor room temperature and visual evaluation D—3D scanning and evaluating the cylinder. *Image* Vesna Pungercar

### 2.2.2 Methodology

The quality of four different cylinders was assessed using visual evaluation and optical 3D scanning methods in four steps (A–D). Step A consisted of mixing materials, step B of 3D printing 19 cylinders, step C of hardening them at indoor room temperature. Step D consisted of optical 3D scanning measurements and evaluating the cylinders (see Fig. 7).

**Step A: Mixing Materials**

Salt and binders were mixed for a minimum of 10 min to ensure a homogeneous consistency. A "KitchenAid Classic 5K45SSEWH" with a capacity of 4.8 L and a tilt-head flat beater proved to have sufficient capacity and strength for the material mixtures (A).

Table 4 shows the following material mixtures CS: Clay, Salt, CSS: Clay, Salt, Straw and SSC: Clay, Salt, Starch with 6 consecutive mixtures (recipes from A–F). Each group starting with recipe A offering the best results from phase one (P1) or being the best mixture from previous tests.

**Step B: 3D Printing**

All test cylinders printed were 10 × 10 × 10 cm. Each cylinder was created from 66 printed layers, each one 1.5 mm high. The circular nozzle had a diameter of 6 mm and the printing speed was set at 40 mm/s. The reference cylinder, purely out of clay, was printed in approximately 8 min, however, the time was raised up to 20 min depending on the material mixture. The printing speed and the extrusion factor were individually controlled and adjusted according to the behaviour of the material. The amount of material usage was estimated at approximately 190 g on average. The base cylinder was prepared and sliced in layers with the software Ultimaker Cura, version 4.9.1 and exported as a G-Code file to the printer. One outskirt ring was set and later removed to ensure a continuous extrusion once the main cylinder started 3D printing (Fig. 8, left image, bottom layer offset from the Test-Cylinder).

**Step C: Hardening at Indoor Room Temperature and Visual Evaluation**

All 19 test cylinders were printed with the same settings for better comparison. However, due to the variation in material mixtures and recipes the overall shape, surface and printability showed significant differences. To further understand the properties of the salt-mixtures, the best printing results were further analysed. One cylinder was taken from each material group (CS, CCS, SSC) and compared. A test cylinder, printed with the same settings and consisting just of clay was added (C) as a reference. Visual evaluation criteria were applied to the material mixtures: pumpability, printed shape maintenance, proper binding time, possibility to build up another layer and surface smoothness.

**Step D: 3D Scanning and Evaluating the Cylinder**

The successfully printed cylinders were stored to dry at room temperature and were scanned with the optical 3D-coordinate measuring device Keyence, VL. Using this

**Table 4** Material mixtures CS: Clay, Salt, CSS: Clay, Salt, Straw and SSC: Clay, Salt, Starch with 6 consecutive mixtures (recipes A–F)

| Group | Recipe | Ratio salt: binder | Salt (g) | Clay (g) | Fresh water (g) | Alcohol (g) | Straw (g) | Starch (g) |
|---|---|---|---|---|---|---|---|---|
| CS | A | 60:40 (1500 g) | 900 | 600 | 140 | – | – | – |
| | B | 60:40 (1500 g) | 900 | 600 | 190 | – | – | – |
| | C | 60:40 (1500 g) | 900 | 600 | 190 | – | – | – |
| | **D** | **70:30 (1500 g)** | **1050** | **450** | **200** | – | – | – |
| | E | 80:20 (1500 g) | 1200 | 300 | 250 | – | – | – |
| | F | 80:20 (1500 g) | 1200 | 300 | 210 | – | – | – |
| CSS | A | 60:40 | 720 | 480 | 180 | – | – | – |
| | B | 60:40 | 720 | 480 | 180 | – | 30 | – |
| | **C** | **64:36** | **840** | **480** | **180** | – | **10** | – |
| | D | 70:30 | 840 | 360 | 180 | – | 10 | – |
| | E | 70:30 | 840 | 360 | 162 | – | 10 | – |
| | F | 70:30 | 840 | 360 | 160 | – | 10 | – |
| SSC | **A** | **60:40 (1500 g)** | **720** | **480** | **150** | **15** | – | **180** |
| | B | 70:30 (800 g) | 560 | 240 | 80 | 8 | – | 100 |
| | C | 80:20 (1000 g) | 800 | 200 | 100 | 10 | – | 125 |
| | D | 78:22 (1150 g) | 900 | 225 | 140 | 10 | – | 140 |
| | E | 75:25 (1000 g) | 750 | 250 | 100 | 10 | – | 125 |
| | F | 80:20 (1000 g) | 800 | 200 | 100 | 10 | – | 150 |

*Source* Authors

equipment it was possible to 3D scan and compare the best prints. The optical 3D coordinate-measuring device allowed us to compare the different cylinders with a precision of 2 μm. The 3D scanning method compares the cylinders digitally, which helps to understand small deflections, inaccuracies or discrepancies at a micro scale.

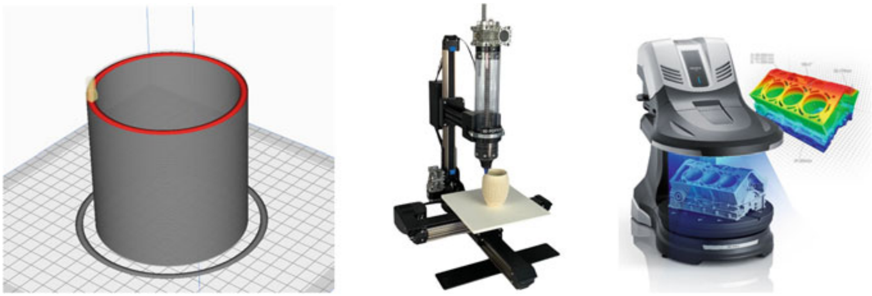


**Fig. 8** Cura-test-cylinder (step B). *Photo* Martino Hutz, Potterbot Micro 10 (step B). *Photo* Potterbot, 3D scanner Keyence VL (step D). *Photo* Keyence

### 2.2.3 Results

#### Step A–C: Preparation and Selection of the Material

All salt mixtures were evaluated in three categories from poor, median to good printing behaviour. Scale 1 represents good printing behaviour, 2 an average performance and 3 a minimum score with bad printing quality. All recipes were first tested with hand injection to understand the 3D printing potential and to save time in the printer set-up. However we observed a significant discrepancy with multiple recipes between the results of the hand injection and the 3D prints. In many cases the hand injection showed good results but could not be printed with the 3D printer. All printed cylinders, even successful prints, showed discrepancies to the original 3D file. All printed cylinders were slightly smaller than the virtual design. During drying, the cylinder dimensions decreased due to humidity loss. The drying time and level of shrinking varied between the mixtures (see Table 5).

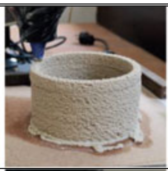
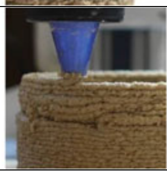
CS-Group: The CS-Group recipes showed different results after being 3D printed. While recipes A–C did not contain enough humidity and clogged in the printing process, recipes E–F showed increasing printing issues with greater water content. Recipe D, being the most successful mixture, was easy to pump by hand injection and had a homogeneous, even surface with a slightly watery consistence. The 3D printed shape was even and air inclusions were covered due to the material consistency. Layers could be built up evenly and the overall surface was homogeneous in all stages. After drying, salt efflorescence occurred evenly on the cylinder (see Table 6).

CSS-Group: Recipes A and B could be printed partially and showed significant problems in stability. Mixtures D–F were increasingly liquid and failed to print full-sized test-cylinders. The best results were achieved with recipe C and a 64:36 ratio. The material mixture printed even layers and was stable. Mixture C showed good results in printing by hand injection as well as with the 3D printer. The overall shape looked good and the full test cylinder could be printed. The layers connected despite the overall rough and porous surface. Due to the added straw, the binding time was significantly longer in comparison to the other mixtures (see Table 6).

**Table 5** Evaluation of the 3D prints and material mixtures

| Name | Recipe | Pumpability | Printed shape maintenance | Proper binding time | Possibility to build another layer | Surfaces | Photo of the best mix |
|---|---|---|---|---|---|---|---|
| CS | A | 3 | – | – | – | 3 |  |
| | B | 2 | 2 | – | – | – | |
| | C | 1 | 1 | – | 1 | 1 | |
| | **D** | **1** | **1** | – | **1** | **1** | |
| | E | 3 | – | – | – | – | |
| | F | 3 | – | – | – | – | |
| CSS | A | 2 | 2 | 3 | 3 | 1 |  |
| | B | 2 | 2 | 3 | 3 | 3 | |
| | **C** | **1** | **1** | **3** | **1** | **2** | |
| | D | 2 | 2 | 3 | 3 | 3 | |
| | E | 3 | 3 | 3 | 3 | 3 | |
| | F | 3 | 3 | 3 | 3 | 3 | |
| SSC | **A** | **1** | **1** | **1** | **1** | **1** |  |
| | B | 1 | 1 | 1 | 1 | 1 | |
| | C | – | – | – | – | – | |
| | D | 3 | 2 | 3 | 3 | 1 | |
| | E | 1 | 2 | 2 | 1 | 1 | |
| | F | 1 | 3 | 2 | 2 | 1 | |

**Table 6** Process material mixture-preparation, Photos: TUM students

| Name | Mixing materials | 3D printing process | 3D printed cylinder | Surface |
|---|---|---|---|---|
| CS |  |  |  |  |
| CSS |  |  |  |  |
| SSC |  |  |  |  |

SSC-Group: Recipe A showed positive print results and was easy to pump both by hand injection and 3D printer. The reference shape could be printed without shifting or distortions. The layers connected easily and therefore created a homogeneous and even surface on the cylinder. Recipes B–F became increasingly weaker. Recipe A produced the best results and was therefore used for future prints within the SSC-Group (see Table 6).

**Step D: Optical 3D Scanning**

The overall scan illustrates the discrepancies with colour coding as well highlights the biggest differences between the four cylinders (C, CS, CSS, SSC) compared to the intended geometry (3D model) (see Table 7). The colour code represents a deformation scale. Dark blue represents a negative offset of −10 mm whereby red indicates the maximum extension of 10 mm. The smallest offset (±0) is represented in light green. Neutral colour indicates that the discrepancy to the base geometry exceeded the 10 mm offset. After optical 3D scanning the images of cylinders, horizontal and vertical cross-section plots (positions 1–4 in Tables 5 and 6), also called surface profiles, were created to quantify the discrepancies. The horizontal section allowed the comparison of the layers width at a given height (50% print) for all prints and visualizes the discrepancy to the outer surface (in yellow) as the reference. The vertical section illustrates the material behaviour and deformation in height. The digital base geometry for comparison was a single surface with the dimensions 10 × 10 cm.

Table 7: Overall scan illustrates the discrepancies to the original geometry (dark blue = negative offset of -10 mm, red = the maximum extension of 10 mm, light green = the smallest offset (±0), neutral colour = the base geometry exceeds the 10 mm offset).

C Mixture: As intended for better comparison the model only showed small deviations. The commercial clay had homogeneous and fine-grained material properties and thus this mixture showed the best results. The scan of the clay-cylinder showed overall small deviation from the base model. Local deflections are due to mechanical inaccuracies or air inclusions within the material. It can be observed that the lower layers extend unevenly due to the material weight. Slight discrepancies are also visible in the horizontal section in comparison to the original base model, with the highest values of 1.458 mm to the cylinder outer surface. The vertical section confirms the slight extension at the base layers, however, stays at a 1–4 mm difference from lower to higher measuring point.

CSS Mixture: The best results of the clay-salt-straw mixtures showed, in the overall evaluation, a straight wall built up and acceptable deformations (see Tables 7, 8). However, the horizontal section shows significant deviations from the original shape. Shifts in a range between 3.121 and 3.751 mm confirm the already visible material roughness. We observed that due to the straw, the material mixture dried and shrank differently than the other test-cylinders. The 3D scan shows interruptions due to the surface roughness as well. The vertical section confirms the uneven surface with significant variations.

**Table 7** Overall scan illustrates the discrepancies to the original geometry (dark blue = negative offset of -10 mm, red = the maximum extension of 10 mm, light green = the smallest offset (±0), neutral colour = the base geometry exceeds the 10 mm offset)

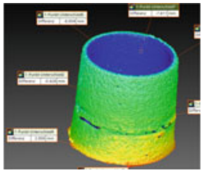
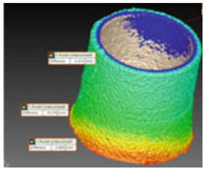
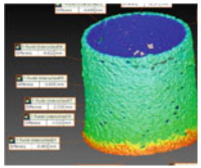
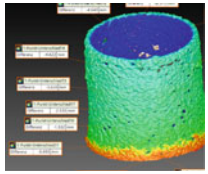
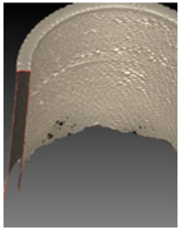
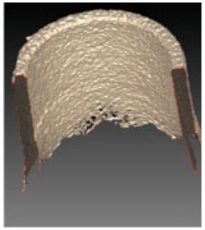
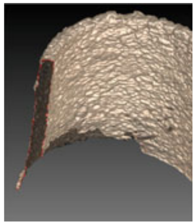
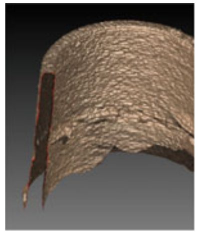
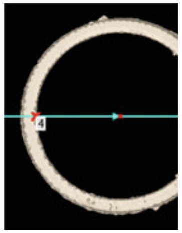
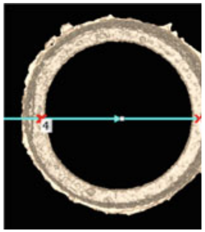
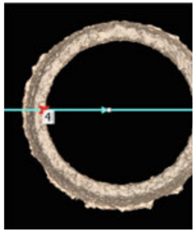
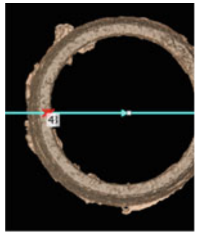
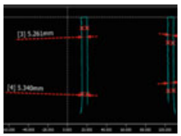
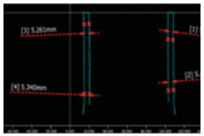
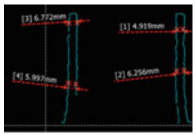
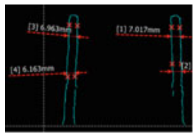
| | C | CS | CSS | SSC |
|---|---|---|---|---|
| Recipe | Clay | Clay, salt | Clay, salt, straw | Clay, salt, starch |
| Discrepancy to the outer surface |  |  |  |  |

**Table 8** Vertical sections illustrate discrepancies to the original geometry

| | C | CS | CSS | SSC |
|---|---|---|---|---|
| Recipe | Clay | Clay, salt | Clay, salt, straw | Clay, salt, starch |
| Bottom left width (mm) | 5.340 | 7.103 | 5.997 | 6.163 |
| Bottom right width (mm) | 5.436 | 6.848 | 6.256 | 7.865 |
| Upper left width (mm) | 5.261 | 6.684 | 6.772 | 6.963 |
| Upper right width (mm) | 5.021 | 6.703 | 4.919 | 7.017 |
| 3D scan section |  |  |  |  |
| 3D scan section-line |  |  |  |  |
| 3D section width (mm) |  |  |  |  |

SSC Mixture: The test cylinder of the clay-salt-starch mixture showed only small differences to the original shape (see Tables 7, 8). Besides mechanical inaccuracies at the lower third, the overall print showed no significant deviations. The horizontal section confirms the overall appearance and captures deviations of only 1.3 mm. The vertical section, due to the starch additive, further proves the good characteristics of the overall surface.

All measurements were compared with the modelled 3D surface (see Tables 7, 8). None of the prints matched the assigned dimensions. This illustrates that during the printing process deflections and distortion occur even without visible damages. With higher heterogeneity and lower humidity the printed quality declines. Larger grains or additives also cause an increase of the deviations. Further, while increasing the humidity improved the printability, it also weakened the substance and thus caused more substantial deviations during the drying process. We noted that all scanned cylinders show an uneven distribution of the material at the base. Our assumption is that this effect, not noticeable to the human eye, was caused by a small inclination of the baseplate. In future research the material properties and behaviour for the 3D printed objects have to be evaluated at a 1:1 scale model and with a bigger sized printer to further develop the mixtures.

### *2.3 Experimental Study 3: Potential Application*

To accompany this research, our chair (EBB) also organized two elective master courses in winter semester 2020 and summer semester 2021, whose focus was to extend the knowledge of salt-mixtures, the historical significance of salt as well as potential applications of the 3D printed salt-mixtures. Research of already established applications of salt in everyday life was categorized to understand future fields of application for 3D printing with salt (see Fig. 9).

Using salt as a local and environmentally friendly resource (geographical usage): This approach is based on the concept of building with local materials in dry and hot areas where little rain falls and salt waste is available from desalination plants or potash mining. Materials found on site can be 3D printed and used for buildings. To find suitable locations for this approach, weather data need to be overlaid onto maps showing areas with salt waste. Once defined the use of salt as a building material can be trialled in the identified regions (see Fig. 9, Left above).

Modular prefabricated elements: 3D printed building-elements fabricated off site from salt-mixtures are installed on sites with the right weather conditions. If the humidity is below 75% but high enough to fuse the salt-crystals without dissolving, the separate building elements will join and work as a unified element (see Fig. 9, Middle below)

Health/respiratory applications: This approach focuses on maximizing salt-rich surface area assuming these particles are released over time due to air circulation in indoor spaces. This concept focuses on the medical application of salt for respiratory ailments (see Fig. 9, Right above).

**Fig. 9** Student work: Shiyu Chen, Kai Lin, Simone Gabbana, Mehmet Yolcu, Katharina Broghammer, Philipp Neumann, Gabriele Mikalauskaite, Pinar Sel, Malaz Attar, winter semester 2020

Salt as air filter: Salt particles in the air are renowned for clearing the lungs and helping asthmatic patients. This principle was the inspiration for the design of a breathing shelter, where the chimney effect was used to intensify the airflow within the space and to strengthen the therapeutic working (see Fig. 9, Left above).

3D printed salt-mixtures for antiseptic applications: A differentiation of surfaces for interior spaces can be utilized in a more meaningful way: The usage of 3D printed salt-containing surfaces can be used for antiseptic purposes; reducing germs on surfaces but also controlling the growth of specific plants. This project focused on green walls, allowing only salt resistant plants to grow (see Fig. 9, Right below).

## 3 Discussion

### *3.1 3D Printer*

All experiments were performed with the Potter Bot Micro 10, which is designed for 3D printing with clay, principally used for the printing of ceramics. The ideal material for 3D printing is, by default and as suggested by the manufacturer, a fine grain clay:

"Maccabees cone 5 stoneware" clay or similar is suggested by the company; the printer is not designed to print concrete or other tough materials by default. A block of clay (10 kg) was separated into smaller pieces with a micro fiber towel placed in between to spread the approximately 350 ml of added water equally in the block of clay. The preparation and soaking process took two to three days.

The chair purchased the Potter Bot Micro 10 for the first test series due to its simple technology and construction. The main advantage for the material-tests is the direct extrusion. A threaded rod, controlled by a stepper motor, presses the material directly through a plexiglass cylinder out through the nozzle onto the printing bed: Other printers use compressed air systems with their elements connected with long tubes to process the material, which could cause clogging and corrosion. The maximum material capacity of the printer's cylinder is 1000 ml and the maximum printing envelope is X-280 mm, Y-265 mm and Z-305 mm. While the cylinder with the material and nozzle only moves vertically, the base/print-bed (266 mm × 266 mm) moves in the X and Y directions to enable full 3D movement. The printer is WIFI controlled with a built-in web interface and can read and print common G-code files. All prints were set up with CURA as slicing software. The speed, Z position and material output can be changed during the print process and adjusted to the material's behaviour.

The printer properties of the Potter Bot Micro 10 and the material-mixtures are highly dependent on each other. The test results derive from the behaviour and capacities of this printer and are likely to change with bigger and more powerful printers. Since the printer is designed to print clay, our salt mixtures (salt-cement, salt-gypsum etc.) showed less convincing results.

### 3.1.1 Print Speed

According to the manufacturer, the print speed of the Potter Bot Micro 10 is recommended within a range of 30 mm/s to 60 mm/s, and a maximum of 130 mm/s. The speed is dependent on the material mixture and needs to be adjusted accordingly.

The fastest speed for a defined print result (see 2.2 Experimental study 2: Salt Cylinder) was reached with processed clay. The main factors behind the need to reduce the print speed were dryness and porosity of the material due to lack of water or increased sand/salt ratio. The lower three layers on the printing bed were printed with only 20% of the defined speed in the original CURA file to ensure sufficient contact to the baseplate. Another reason to limit the print speed is the printer construction: If the speed increases, the X–Y controlled base starts shaking and inaccuracies in the print appear; detached and crooked layers that eventually cause the print to collapse. Even though the speed had to be slightly adjusted in each print, a speed of 25–30 mm/s was proven to print the best results with all material mixtures.

### 3.1.2 Nozzle

The Potter Bot Micro 10 comes with a range of four anodized aluminium nozzles (3, 4, 5, and 6 mm). However, 3D printing with salt mixtures revealed that only the 6 mm nozzle was appropriate as smaller nozzle sizes caused clogging. Due to an increased instability of the clay caused by adding salt (see 2.2 Experimental study 2: Salt Cylinder) narrower layers resulted in shaky and collapsing test cylinders. Material mixtures with sand components (sand grain between 0.1 and 0.4 mm) caused immediate clogging even with the 6 mm nozzle. Sand grains (in combination with clay and salt) interlocked immediately as pressure on the nozzle was increased.

### 3.1.3 Printed Layer Height

All test cylinders were printed with a layer height of 1.5 mm since thinner layer heights resulted in the overlapping of material. In relation to the print speed and nozzle size the salt-mixtures were too rough to print clean layers and therefore the material was pushed outwards significantly, increasing the layer width as a consequence. Thicker layers resulted in lack of contact between the each other and led to unsatisfactory test prints.

Additionally, we carried out tests printing with “falling infill”. The Z height was moved upwards by about 200 mm in the source code so that the salt-mixture fell into a prepared mould placed on the printing bed. The shape of the mould needed to match the print bed dimensions but could be individually modified in height.

### 3.1.4 Printing with Inclination

Several tests were made with different material-mixtures. However, the recommended inclination for PLA (Polylactic Acid, most commonly used for small scale 3D printing) of 45° could not be achieved with any of these. When increasing the salt-ratio the mixtures became more and more fragile and therefore the maximum inclination achieved was approximately 20° (depending on the complexity of the shape as well as the water and salt content).

### 3.1.5 Replacing Printing Material

Changing the printing material requires demounting and replacing the cylinder, including the removal of the top-part (motor with threaded rod and plate for material compression) and bottom-part (component with nozzle) of the cylinder attachments, each connected with eight screws. Since the cylinder material capacity is limited to 1000 ml, larger 3D prints had to be paused while the material was refilled. The cylinder position needed to be marked manually to retrieve the exact Z position of the nozzle and the tracing of the refill had to be done by hand since the main print program could not be resumed once paused. This caused discontinuity within the shape as well as of the material finish which was taken into consideration for the material thickness and the design. Larger models needed a wall-thickness of a minimum of 25–40 mm to enable the precise continuation of the print with the second refill.

#### 3.1.6 Printing Scale

The maximum printing envelope, described by the manufacturer as X-280 mm, Y-265 mm and Z-305 mm could not be fully utilized in any of the test-prints. Only prints with maximum dimensions of X-250 mm, Y-250 mm and Z-250 mm showed positive results. We observed that large prints approaching the print size limits became inaccurate at the edges. However, in most test-prints it was the material mixtures that limited the overall model dimensions and not the printer. The 3D prints progressively deformed with higher salt ratios in the mixtures and when increasing the overall printing height.

#### 3.1.7 Printing Time

The test cylinders were prepared with height and diameter of 100 mm. The cylinder was printed with a single-layer wall build-up and therefore no infill. In the samples, the layer height was set to 1.5 mm as to allow rougher material-mixtures to be built up in continuous layers. The single layer wall line was set to a width of 6 mm with a 6 mm nozzle. The print speed was set to 30 mm/s, which resulted in an estimated printing time for the full test cylinder of 19 min (see 2.2 Experimental study 2: Salt Cylinder).

### *3.2 Materials*

#### 3.2.1 Salt and Binders

Salt is too porous to be printed alone and requires the utilisation of a binder to hold the salt crystals together in the material extrusion process. Different material tests with our printer showed clay to be the most appropriate binder. Already in the first phase of the experiments, salt-clay (SC) mixtures showed the best printability. However, the SC 3D printed objects (in comparison to the solid clay mixtures) often showed cracks, voids and roughness on the surface as result of a decrease in stiffness. So, in the second phase of the research we experimented with the addition of starch or straw to SC mixtures. While the SC with starch behaved better (stiffness and ductility were improved), SC with straw was in most cases too hard to press through the nozzle of the printer. The straw absorbed water to an unacceptable degree such that the mixture was no longer printable. Consequently, only very small amounts of straw could be added.

The experimental studies with other binders showed gypsum to have a too short a setting time, concrete to have a too high amount of aggregates and starch to be too fluid. We expect that with adapted additives (super-plastifier, fly ash, short fibres, retarder) or the application of heat, the printability (flow, compressive strength, setting and drying time) could be improved. However, no such studies were carried out.

### 3.2.2 Amount of Salt in the Printing Mortar

The main goal of the research was to increase the resource efficiency by using the highest possible amount of salt in salt binder mixtures and still obtain the desired printing properties. The highest amount of salt was reached in the salt-clay mixtures with the addition of starch. The optimal mixture consisted of 57% salt, 24% clay, 88% starch, 8% water and 0.8% alcohol. The ratio of salt and binder here was 70:30, all other mixtures had lower salt/binder ratios.

### 3.2.3 Surface

Salt crystals on the surface of the 3D printed layers not only contribute to an attractive surface, but may also have an effect on health (not yet scientifically investigated) and hygrothermal properties. Higher levels of surface salt crystals could enhance the infiltration of microscopic salt particles into the indoor air with a positive influence on respiratory health. At the same time, the uneven and rough surface will store heat and humidity more rapidly (max 75%) than a smooth one. However, the prevalence of salt crystals on the surface did not only depend on the salt content in the mixture but also on the additives. Although the salt-clay-starch mixtures contained the highest amount of salt, crystallisation was almost undetectable on the surface (due to the starch's properties). In fact, the most visible crystallisation on the surface was observed with the highest water content in salt-clay mixtures without additives.

### 3.2.4 Water Content

In all our studies, the water content had to be adapted to the salt content as well as the types of additives and binders. The highest water content (with still acceptable printability) was observed in the salt-gypsum (SG) mixtures of the first phase. In salt-clay mixtures in the second phase the amount of water could be raised (up to 13% mass content) by adding straw and was lowest (8% mass content) when adding starch. Finally, with more salt in the salt mortar the water content could be increased. However controlling the printing mortar properties by addition of salt and water were challenging because the salt/water ratio was never linear.

#### 3.2.5 Reinforcement

Reinforcement (straw) was used in the second phase of the studies to obtain better control of cracks after the drying period. We found that the mortar was only printable with the addition of small amount of straw (up to 0.7% mass content). Already in the mixing phase, the straw reinforcement absorbed a lot of water and during the 3D printing process the mortar often became too dry to print with. The research of a variety of reinforcing fibres and a closer control of their impacts is thus recommended for future studies.

#### 3.2.6 Drying

All 3D printed objects were dried at room temperature or in the oven at 90 °C, and it became apparent that the drying process influenced the shrinkage of the objects: with more cracks appearing with longer drying periods. The shortest drying period was recorded for salt-gypsum mixtures and the longest for salt-clay mixtures with starch. Drying an object in the oven accelerated the vaporization of water and caused more salt efflorescence on the surface.

### *3.3 Other Parameters*

#### 3.3.1 Full-Scale Printing with Salt

The experiments explored the use of salt in a small-scale printing process. Further optimization of the salt printing mortar is needed for full-scale printing. Small-scale printing results will probably not be directly applicable to a full-scale print due to a different "relationship" between printer and material. In this study we found that the print mortar had to be adapted to printing properties and to the printer itself. For example a mortar containing too much salt was impossible to push through the printer‘s nozzle. Consequently, the amount of salt (maximum aggregate size of the printing mortar) was reduced for better printing results. A similar need for adaptations of the printing mortar in full-scale printing can be expected. The properties of the mortar will have to be controlled by different salt/binder ratios or by the inclusion of additives and adjusting the drying and hardening process (cracks should be minimized and compressive strength for maintaining the intended shape must be ensured).

#### 3.3.2 Influence of Salt on the Compressive Strength

The compressive strength of the 3D printed objects was not specifically investigated in these experiments because the compressive strength of salt-gypsum and salt-clay mixtures have already been tested in previous studies on salt material properties. Compressive strength tests were performed on cuboids of 40 × 40 × 160 mm following the norm DIN EN 13,454–2. The testing cuboids were placed in a climate room at 60% RH and 21 °C, which negatively influenced the values: All mixtures were extremely porous, almost impossible to test and lost up to 96% of their compressive strength in comparison with the reference (100% gypsum or 100% clay). As a consequence, some salt-clay mixtures were put into the climate chamber again as an experiment for 24 h at 40 °C before testing. The results showed that the strength values of dried salt-clay mixtures (30% salt and 70% clay) increased up to 140% compared with the reference (100% clay). Considering the effects of relative humidity on compressive strength it is thus preferable to use structural salt mixtures in dry and hot climate zone or conditions.

### 3.3.3 Surface Treatment and Stucco

The process of additive manufacturing produces inherently textured surfaces. The layers, depending on the material, nozzle size and layer height, are staggered horizontally and therefore visible on the outer surface. Adding salt to other materials triggered an increase of porosity and surface roughness, which will have a major influence on the design of potential full size building elements. Depending on the application, the surface would need to be protected from potential damage like humidity, rain or manual impact. The type of protection will need to be analysed in a separate study.

### 3.3.4 Prefabrication, Field Factories and On-Site Printing

Different construction methods for 3D printing with salt can be considered and will need to be studied. The printing method will depend on the field of application and will have to comply with the constraints of the 1:1 scale printer. Prefabricating 3D printed building parts will have the advantage of a controlled production environment which allows for more complexity and precision of the printed geometry (see Fig. 10). As recently applied in the 3D printing industry for buildings, the printer could alternatively be mounted to print on site. This would especially be attractive for remote areas with high salt resources.

## 4 Conclusion

In this research three consecutive studies were undertaken to analyse salt mixtures for additive manufacturing in paste extrusion. The intent of this research was to find potential for the use of more salt in the building process. Salt is increasingly becoming an environmental threat as a by-product in desalination plants as well as potash production. However, salt has high potential due of its over-availability and

**Fig. 10** Remote 3D printing at Chaka salt lake, master Thesis, Kai Lin, summer semester 2021, TUM

positive properties such as storage of humidity and heat as well as potential positive impact on respiratory health.

The analysed mixtures were made with a small but significant fraction of potential additives, this can be extended with cement, resins or other materials. The research showed promising results and succeeded in integrating up to 70% of salt in the 3D printed material mixtures. However, the tests were limited due to parameters as lab-space, the available 3D printer and the testing facilities. Most of the printed mixtures were less stable with increased salt content, although some results (see Sect. 3.3.2) had an even higher compressive strength, so the need for additives has to be clarified. Straw, as hydrophilic additive, caused increasing surface roughness and segmented layers. The question of the dissolution of salt at above 75% humidity remains to resolve; this can be improved with surface treatments and sealants. It can be seen that by working with 3D printing as new construction method new approaches have to be considered for the salt-mixtures. Prefabrication of "smarter" surfaces or systems for on-site construction is likely to become a relevant field of application. The absence of steel reinforcements in the 3D printing process allows salt to reveal its positive properties instead of causing unwanted corrosion. Finally, 1:1 scale samples need to be printed to fully understand the potential of 3D printing with salt.

**Declaration of conflicts** No conflicts.

**Authorship Contributions** Vesna Pungercar: Conceptualization, Methodology, Formal analysis, Investigation, Paper Layout, Resources, Writing - Original Draft (Abstract, 1. Introduction, 2 Experimental studies, 2.1 Experimental study 1: Salt/Binder, 2.2 Experimental study 2: Salt Cylinder, 3.2 Materials, 3.3.1 Full-scale printing with salt, 3.3.2 Influence of salt on the compressive strength, 6 Publication).

Martino Hutz: 3D print strategy, Visualization, Formal analysis, Investigation, Resources, Writing - Original Draft (2.2 Experimental study 2: Salt Cylinder, 2.3 Experimental study 3: Potential Application, 3.1 3D printer, 3.3.3 Surface treatment and stucco, 3.3.4 Prefabrication, field factories and on-site printing, 4. Conclusion).

Florian Musso: Conceptualization, Writing: Review and Editing (All chapters).

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# 5 Appendix B: Signed declaration of contribution for 4 Papers

# 6 Appendix C: Material mixtures

Salt, as a waste product of seawater desalination, can contribute in combination with binders. It can also take on climate-regulating functions. In this research project (founded by Fritz und Trude Fortmann Stiftung) salt is being studied in combination with binders (see Figure 18). The goal of this study was to evaluate how salt influence the quality of salt-gypsum mixtures. The experimental study deals with defining mixing ratio of salt and binders and testing compressive strength. The considered methods were found in the literature, but are not written for salt because there are none identified by authors. Compressive strength tests were performed according to norms DIN EN 13454-2 and SIST EN 196-1:2016 at MPA (Materialprüfungsamt für das Bauwesen) at the Technical University of Munich, Germany.

**Figure 18.** The first test specimens of salt and the different binders (source: Vesna Pungercar).

**Gypsum-salt mixture:**

Gypsum production has come under criticism because of the energy required for burning and the mining processes that alter the landscape. Resources such as FGD gypsum, which currently cover around 50% of Germany's gypsum requirements, are disappearing as coal combustion and flue gas desulfurization are phased out. Different mixture of gypsum, salt and Ca Alginates (0.0% salt+100.0% gypsum, 30.0% salt + 70.0% gypsum, 20.0% salt + 80.0%

gypsum, 30.0% salt + 70.0% gypsum + 5.0% Ca-alginate, 30.0 % salt +70.0% gypsum + 10.0% Ca-alginate, 30.0% salt + 70.0% gypsum + 15.0% Ca-alginate) have been explored (Figure 19). Microscopic analysis of the microstructure has shown that the structure of gypsum changes when combined with salt. In the case of gypsum without salt, smaller crystals with the high pore volume are observed. The surface shows an open-pored structure, which also represents a potential for storing the air humidity at high room air humidity. Gypsum with salt has larger crystals with smaller pore volumes. Alginate increases viscosity due to gelation. Emerging material is lighter and the crystals are more strongly bonded (Figure 18).

**Figure 19.** The test specimens of salt, gypsum and Ca-alginates with the different mixing ratio (from left to right): 0.0% salt + 100.0% gypsum, 30.0% salt+70.0% gypsum, 20.0% salt + 80.0% gypsum, 30.0% salt + 70.0% gypsum + 5.0% Ca-Alginate, 30.0% salt + 70.0% gypsum + 10.0% Ca-alginate, 30.0% salt + 70.0% gypsum + 15.0% Ca-Alginate.

**Clay-salt mixture:**

Different mixtures of clay, salt and Ca-alginate (0.0% salt+100.0% clay, 10.0% salt + 90.0% clay, 20.0% salt + 80.0% clay, 30.0% salt + 70.0% clay, 40.0% salt + 60.0% clay, 50.0% salt + 50.0% clay, 50.0% salt + 50.0% clay + 5.0% Ca-alginate, 70.0% salt + 30.0% gypsum + 5.0% Ca-alginate, 90.0% salt + 10.0% clay + 5.0% Ca-alginate) were studied. Analysis of the microstructure by microscope showed that the structure of clay changes when combined with salt. Clay with salt produces larger crystals with larger pores than clay without salt. The addition of Ca-alginate in the clay-salt mixture affects the surface structure and weight of the material. There is less efflorescence on the surface and the material is lighter. The content of Ca-alginate and calcium in the material leads to an increase in viscosity (Figure 20).

**Figure 20.** The salt and clay test specimens with different mixing ratios (from left to right): 0.0% salt + 100.0% clay, 10.0% salt + 90.0 % clay, 20.0 % salt + 80.0 % clay, 30.0% salt + 70.0% clay, 40.0% salt + 60.0% clay, 50.0 % Salt+50.0% clay.

### Salt-polysaccharide mixture (corn starch, calcium alginate):

Various mixtures of salt and polysaccharides (70.0% salt + 30.0% corn starch, 80.0% salt + 20.0% gypsum, 90.0% salt + 10.0% corn starch, 86.0% salt + 13.0% Ca-alginate, 90.0% salt + 5.0% Ca-alginate) have been researched. Polysaccharides are used in the food industry to improve the quality and texture of a variety of foods. It was found that polysaccharides can also be blended with large amounts of salt. Examination of the mixture for surface quality, bulk density and porosity shows a significant change. Salt mixed with water is very porous and unusable after drying/water evaporation. Salt mixed with water and polysaccharides holds together and is usable. However, the optimal mixtures should be further analyzed (Figure 21).

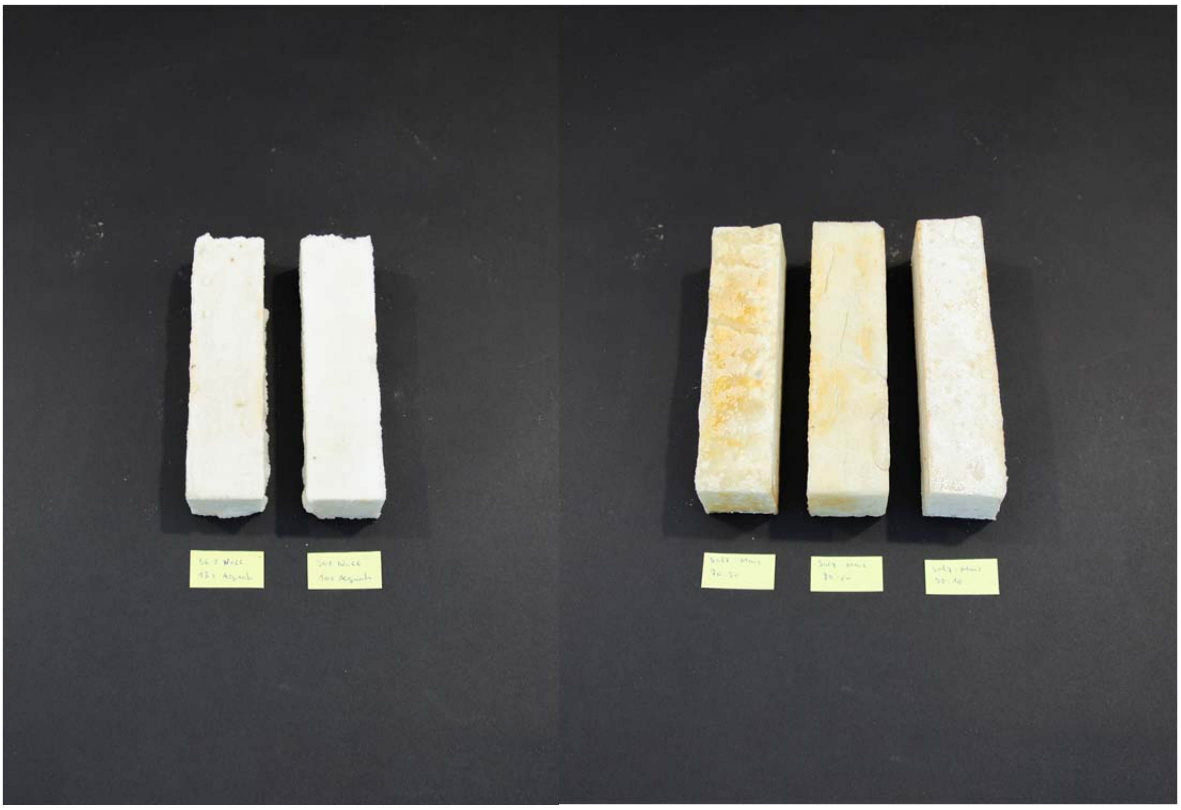


**Figure 21.** The salt + corn starch test specimens with different mixing ratios (from left to right): 86.0% salt + 13.0% Ca-Alginate, 90.0% salt + 5.0% Ca-alginate, 70% salt + 30% corn starch, 80% salt + 20% gypsum, 90% salt + 10% corn starch.

**Bulk density of salt mixtures:**

The bulk density of the materials is measured in the fresh and dry states. The fresh bulk density was taken from the molds 1 day after mixing and measured. The dry bulk density was stored at 21°C and 60% humidity for 5 months and then measured again. The fresh bulk densities for the salt composites with clay, gypsum, and cornstarch were 1544 kg/m$^3$ - 2025 kg/m$^3$, 1394 - 1907 kg/m$^3$, and 1655 - 1673 kg/m$^3$, respectively. The highest bulk density in the fresh state is observed for clay, and the lowest for gypsum. A similar situation can be observed in the dry state. The dry bulk densities for the salt composites with clay, gypsum and corn starch are 1508kg/m$^3$ - 1840/m$^3$, 1053 - 1792kg/m$^3$ and 1463 - 1584kg/m$^3$, respectively. The bulk density is lower in the dry state than in the fresh state. Experimentally, after storage in the mortar laboratory (21°C, 60% RH), the 5 salt clay composites were additionally stored in the heat chamber at 70°C and 30.0% humidity for 24 hours. An increased decrease of the bulk density up to about 50.0% was measured. This showed that the bulk density is most dependent on the water content in the total mass and in the environment. Further laboratory tests should be carried out to investigate in detail the influence of water content, drying method and ambient conditions on bulk density.

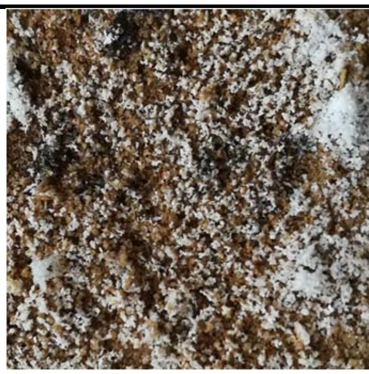
**Compressive strength of salt mixtures:**

The compressive strength of salt composites is determined according to EN 196-1 (Test methods for cement - Part 1: Determination of strength; German version EN 196-1:2016). The laboratory where the specimens are made had a temperature of 21°C and a relative humidity of at least 60%. The compressive strength of clay with different salinity was very low (4.6N/mm$^2$ - 21N/mm$^2$) after 5 months of storage in the laboratory. Therefore, it was decided to dry the clay salt materials experimentally in the heating chamber at 70°C and 30.0% humidity for 24 hours. The 42-fold improvement in compressive strength (196N/mm$^2$ - 1177N/mm$^2$) shows that compressive strength is also strongly dependent on ambient temperature and humidity, and that clay-salt material is best suited for dry climates. The compressive strength of gypsum-salt material stored in the laboratory was measured between 10 and 51N/mm$^2$, which is twice that of clay. In the case of the gypsum-salt material to which alginates were added, the addition further increased the compressive strength. For further investigations, it was decided to use the gypsum-salt mixture. In the next phase, 4 specimens (100.0% gypsum, 90.0% gypsum + 10.0% salt, 70.0% gypsum + 30.0% salt, 50.0% gypsum + 50.0% salt) were dried and tested for compressive strength at 20°C and 99.0% relative humidity for 1 day and at 20 °C and 65% relative humidity for 6 days. Since the specimens with 50.0% gypsum and 50.0% salt were still too liquid after 7 days, the specimens were dried for another 7 days at 40.0°C and 65.0% relative humidity. After that, the compressive strength was tested again. The mixture of 70.0% gypsum and 30.0% salt proved to be the variant with the highest density (1854kg/m$^3$) and the highest compressive strength (2.6 N/mm$^2$) among the salt-gypsum test specimens.

**Efflorescence:**

Efflorescence occurred at different times and intensities in all material mixtures. In the clay salt materials, efflorescence was visible after a short time and developed as small snowflakes. The efflorescence occurred very strongly due to the contrast between the colors of the clay and the salt. On the gypsum salt material, the efflorescence appeared later and usually appeared as very thin encrustations on many areas of the surface. The salt efflorescence is less visible and shimmers very subtly in the light reflection. Starch-salt materials allow artistically attractive efflorescence to be observed even inside the material. Small blooms form on the surface and coalesce into larger structures. With increasing salt content in the mixture, only salt crusts can be observed on the surface (Table 12).

**Table 12.** Specimen – surface (efflorescence).

| Starch-salt efflorescence | Gypsum-salt efflorescence | Clay-salt efflorescence |
|---|---|---|
|  |  |  |
|  |  |  |

# 7 Appendix D: Study of the influence of salt on performance during climate fluctuations.

In this study the variations in weight of three materials (salt, gypsum, salt-gypsum) during the humidity fluctuation at two different temperatures was investigated to analyze durability of materials for indoor application and collect the hygrothermal information for comparison with simulation/experimental results in chapter 2.

**Method:**

Experiment followed in two steps. At step A, each material was preconditioned in the climate chamber (for moderate climate zone: 30% RH and 21°C and for tropical climate zone: 30% and 27°C) for 24 hours. At step B, only one material was placed on the weighing machine in the climate test chamber, which recorded the weight at minute intervals. At the same time T and RH in the climatic chamber were set and measured by data logger in order to compare weight and climate data changes directly. Relative humidity is an important factor that affects salt, which dissolves at more than 75% RH. Therefore, the humidity fluctuation was set in the range of 30–80% to experimentally study if salt materials really dissolves, as defined in the literature for pure form of salt [68, 152]. The temperature was set at 21°C to predict an indoor environment in moderate climate zones and at 27°C for tropical climate zones. The test specimens were exposed to the same 6-hour fluctuation cycles with starting 30% RH at a constant temperature. A total change in RH was 50% (from 30 to 80%) in a three-hours, so that the material has enough time to react to changes in the climate chamber and to show potential damage. For this purpose, four de-humidification and different humidification time intervals were conducted. The considered experimental method was similar to proposed by Holl [153].

**Results:**

The results (from Figure 22 to Figure 27) in the graph show on the left side the values of temperature and relative humidity measured in the climatic chamber and on the right side the values of mass change of the material during the measurements. The graphs below refer to the duration of the test. It can be seen that the small climatic differences are due to the climatic chamber and each material was tested separately. The results show that as the relative humidity and temperature change, the mass of the test material also changes. However, the materials responded differently due to their different hygrothermal properties. Gypsum shows the largest mass changes at 21°C (from 0.0g to 3.65g) and at 27°C (0.00g to 3.26g). Salt shows the least mass changes at 21°C (from 0.00g to 3.60g) and at 27°C (0.0g to 2.03g). Salt-gypsum has values between salt and gypsum at 21°C (from 0.0g to 1.94) and at 27°C (0.00g to 1.89g). Gypsum is the most "diffusion-open" material.

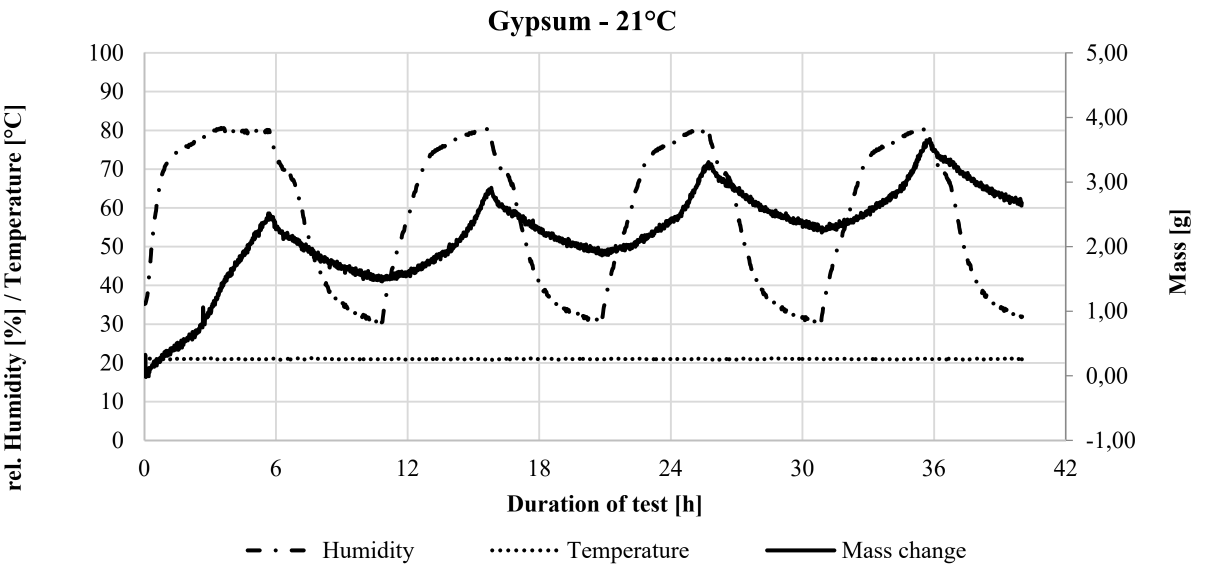



**Figure 22**. The change in weight of gypsum at 21°C and relative humidity (30.0%-80.0%).

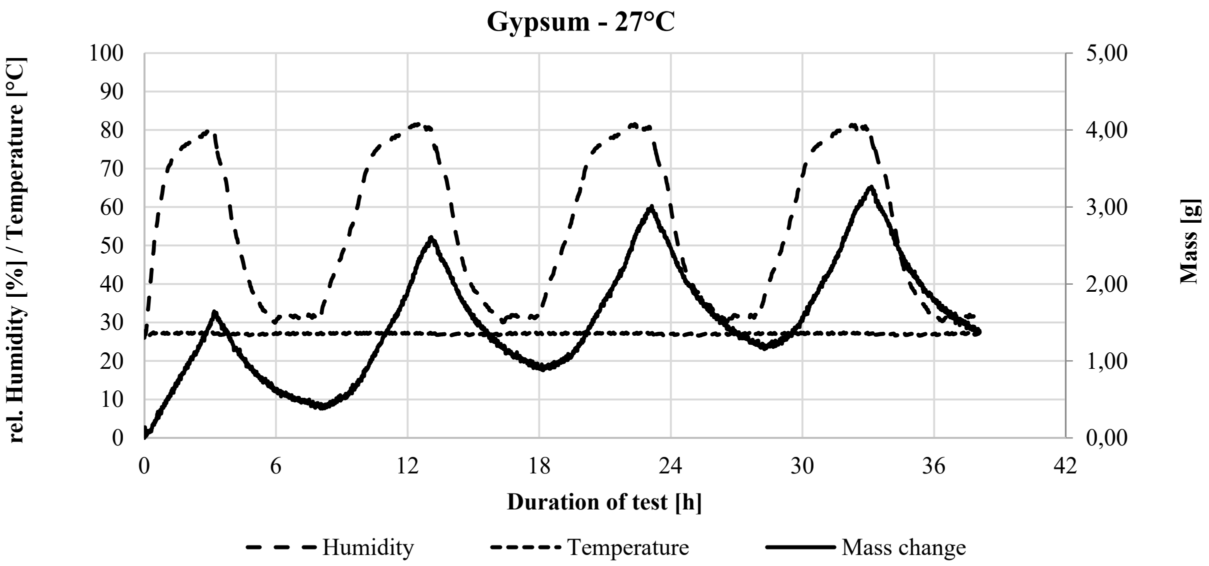



**Figure 23.** The change in weight of gypsum at 27°C and relative humidity (30.0%-80.0%).

All materials showed the same fluctuation: a large increase in weight when relative humidity increased and a large loss in weight when relative humidity decreased. At a temperature of 21°C, the increases and decreases were smaller for all three materials than at a temperature of 21°C. When moisture was absorbed and released after each relative humidity variation, it can be observed that for salt, the weight increased only slightly compared to the initial condition. For gypsum, the weight always increased after the desorption-adsorption cycle, illustrating the wetting of the materials. Salt-gypsum test material also wetted over time. But not as much as gypsum and not as little for salt. Even thought the relative humidity of the climate chamber exceeded over 75% (critical value for salt) there was no water or damage on the salt noticed.

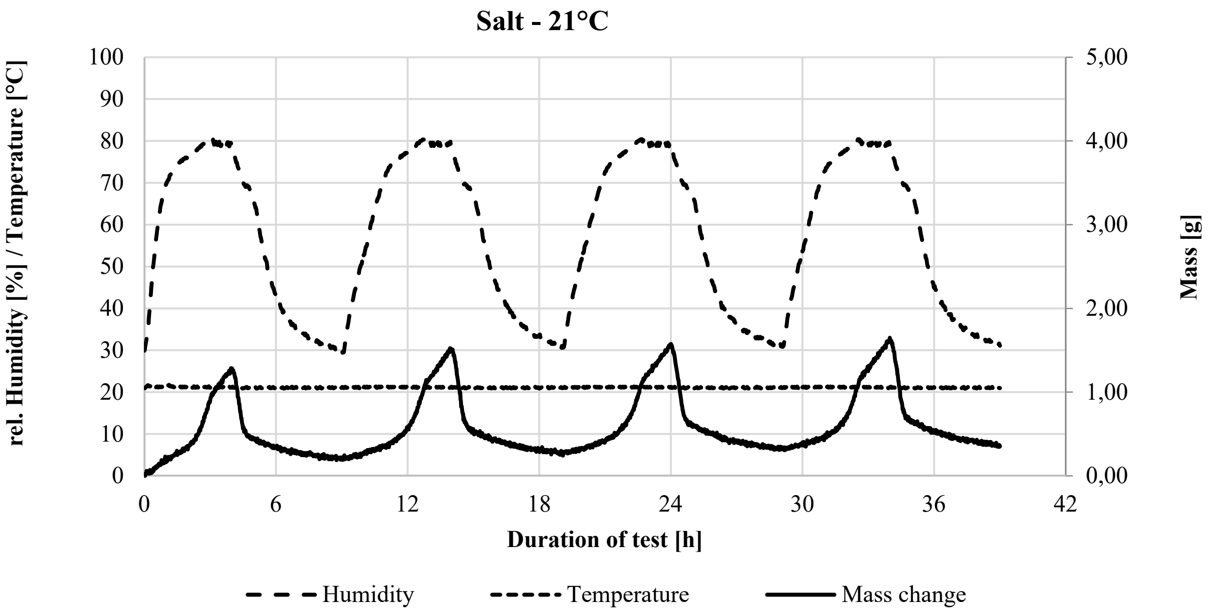



**Figure 24**. The change in weight of salt at 21°C and relative humidity (30.0%-80.0%).

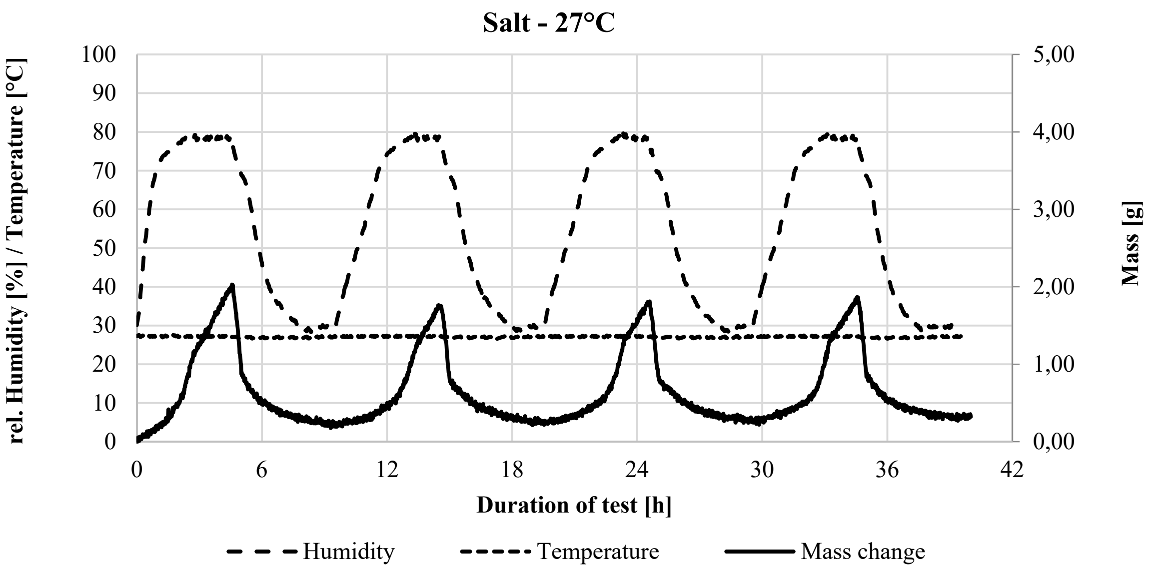



**Figure 25**. The change in weight of salt at 27°C and relative humidity (30.0%-80.0%).

This study shows that although the relative humidity in the climatic chamber was above 75% (critical value for salt), no water or damage to the salt was detected, as described in the literature. Salt and gypsum responded with different variations to an increase and decrease in relative humidity due to their hygroscopic properties. Salt was less affected by changes in relative humidity due to its lower porosity and moisture diffusion. This means that salt does not change its behaviour as much as gypsum and is likely to suffer less damage over time than gypsum. These results are consistent with the simulation and experimental study from chapter 2, but further studies with longer test durations and different fluctuations should be conducted to obtain more accurate information.

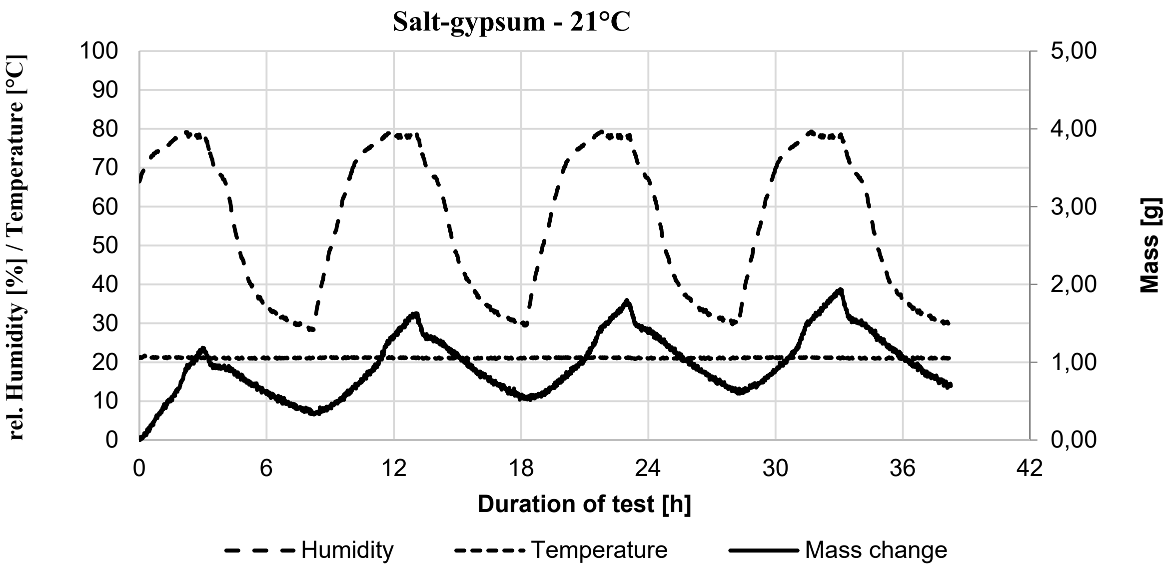



**Figure 26.** The change in weight of salt.gypsum at 21°C and relative humidity (30.0%-80.0%).

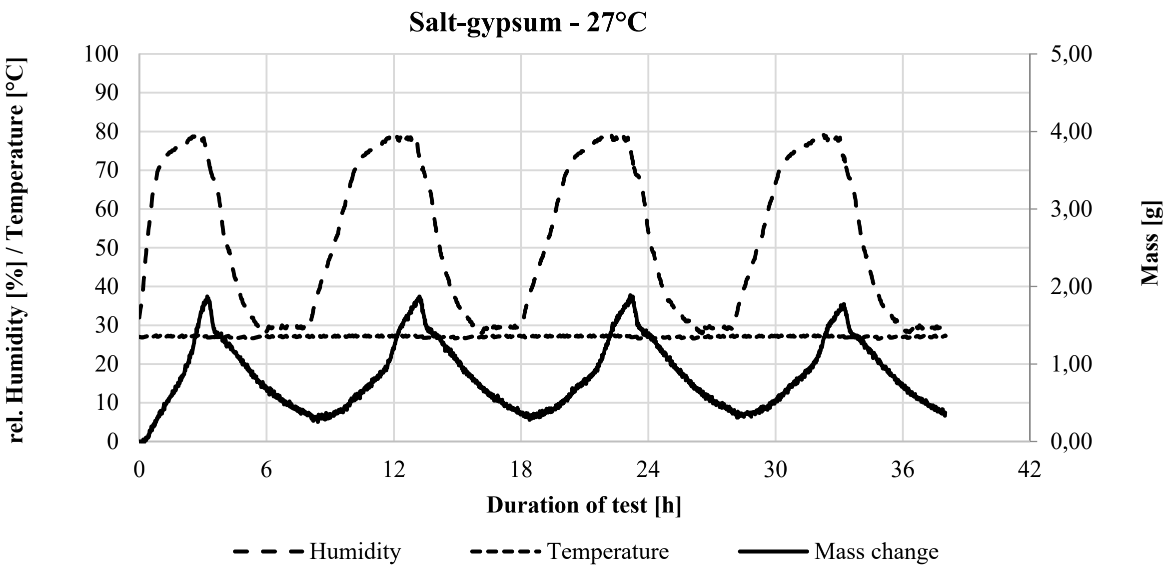



**Figure 27.** The change in weight of salt.gypsum at 27°C and relative humidity (30.0%-80.0%).