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BACHELORS THESIS

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DECLARATION

I, Josemar Bruno da C. M. Guedes, thus certify that the bachelor thesis submitted for evaluation was written entirely by me, with my supervisor, Doc Ing. Alena Vimmrova, PhD. Whatever usage of other authors' works (e.g., ideas, figures, text, tables, programs) inside it is duly acknowledged at the time of use. A complete list of the sources used is supplied.

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I would also want to thank all the teachers in the materials department for all their insights and guidance for this thesis, which made it possible for me to write about this engaging topic.

Design of gypsum-based composites with wooden waste

Abstract

This thesis describes an experimental study on an innovative composite material, prepared from gypsum and wood waste-gypsum. The basic properties of gypsum binder and the organic material, which can be used in gypsum as fillers are described in the theoretical part. During experiments the flue gas desulfurization gypsum was combined with wood waste from the sawmill after cutting, planning, and sanding of timber. The wood waste was added to the gypsum binder in different amounts in order to find the optimal combination for use not only in Czech Republic but also in some Africa countries. It was found that composite with 10% of wood waste has sufficient properties to be used as a construction material for less demanding purposes. The bulk density of this material was 951 kg/m^3, compressive strength was 2,8 MPa and thermal conductivity 0, 27 W/m.K. The material with 20% of wooden waste can be used as a thermal insulating material. By the suitable combination of the gypsum and wood waste the cheap and ecologically friendly material with desired properties can be prepared and by using the local wood waste it can be used also in Africa countries.

Keywords: Gypsum, wood waste, wood-gypsum composite, recycling, testing, technical properties.

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1.0 Introduction

In sulphate minerals, gypsum ($CaSO_4.2H_2O$) is one of the most common. It is also known as satin spar (a fibber containing a variety of gypsum), alabaster (a fine-grained form of gypsum), and selenite (a form of gypsum having colourless transparent crystals). [1] The word gypsum is derived from the Greek word γύψος (gypsos), "plate.".[2] The word plaster of Paris came from the quarries of the Montmartre district of Paris, where gypsum was mined for different purposes. It was known as spærstān (spear stone) in old English, mentioning its crystalline spur. When water is added to the plaster of Paris, it becomes gypsum that causes the material to become hard or set, so this property of plaster of Paris is helpful for construction and casting purposes. Most gypsum is found in massive thickness forms associated with limestone and shale. At thrust faults and tectonic dislocations, most of the layers of deposits of alabaster gypsum can be found. In the building industry and production of cement, gypsum is considered an essential raw material. It was also known as lime sulphate or Sulphate of lime in the 19th century. When Egyptians came to know the properties of gypsum, they used it in the construction of pyramids. As most chemists see this name, few people do not know hydrous calcium sulphate

Fig.1: Gypsum selenite from Brazil from [from https://www.mindat.org/gm/1784]

2.0 Gypsum

In sulphate minerals, gypsum is found as a common mineral. It is seen as sedimentary deposits in the form of shale, limestone, clays, and sandstones. Commercially the term gypsum is used for calcium sulphate dehydrate ($CaSO_4 2H_2O$). From all over the world, the United States produces 20 % of gypsum, the highest rate of gypsum production. Since the earliest recorded history, gypsum has been used. Greeks, Chinese, and Assyrians used gypsum for decoration and carving purposes.[3] During the construction of pyramids in the ancient Egyptian era, it was used as mortar. In the olden times of Greek, Theophrastus provided an idea about the preparation of gypsum plaster by burning gypsum. It consists of hydrated calcium sulphate. It is a natural mineral salt. There is a resemblance between gypsum and anhydrite. The chemical formula for gypsum is ($CaSO_4.2H_2O$), while the chemical formula for anhydrite is $CaSO_4$. It shows that gypsum contains two water molecules, while anhydrite has no water. It is found in grey or soft white colour, is present in the form of layers in sedimentary accumulations. Gypsum is an evaporate mineral. In salt lakes where water evaporates and salts are left behind, sulphate can be found there. When hydration of anhydrite occurs due to groundwater and surface water, gypsum is formed. dolomitic limestones and limestones are also a source of gypsum.

2.1 Sources

2.1.1 Natural sources

Naturally, gypsum can be found where thick beds and layers of rocks are present.[4] Calcium and sulphate minerals are present in high amounts in ocean water, so gypsum can be found in lagoons because ocean water evaporates slowly when water evaporates minerals left behind. All over the world, gypsum deposits occur, but the United States, Spain, Turkey, Russia, and Thailand are the top countries in producing gypsum products, although gypsum resources have been identified in certain West and Central African nations such as Mali, Nigeria, and Angola, there are economically developed gypsum mines in the western region of Africa to date. Gypsum requires a long-term period to be dissolved in water, so there are rare chances to find gypsum in powder form. Mostly it can be found in crystal form. Gypsum is available in many forms. It is not coloured or white but can be light brown, grey, yellow, green, or orange due to the impurities. Single, well-developed crystals can be blocky with a sloping frame of a parallelogram fragmented. Twisted crystals are common and often form part of the "fishtail." Many gypsum crystals that show through 2 m or more in length can be found in the Cave of Sword, Chihuahua, Mexico. Gypsum occurs in wide beds formed by the evaporation of ocean water. It also occurs as a product of converting sulphides to metal deposits and as volcanic deposits. Gypsum crystal was found 3 meters in length and 45 cm in diameter in the Braden mine of Chile. This piece of gypsum is one of the largest pieces of gypsum all over the world. The bulk of gypsum has been found on Mars as well. Mined gypsum can be found in North America, and there are deposits of gypsum from Texas too. Other minerals and materials are mixed with mined gypsum, such as trace elements and a few amounts of soil and sand particles. In each deposit, trace elements vary from boron to iron and arsenic. It is safe to use mined gypsum.

2.1.2 Sources in my country (Angola)

The largest deposits of gypsum in Angola can be found in Angola's Baia dos Tigres, or Great Fish Bay, in the Namibe province. On the eastern side, there was once a tiny peninsula with a well-established fishing community called Tigers. The water boundary was broken when the ocean came through the isthmus side of the peninsula in 1962. It was titled Tigers Island, which is Angola's largest island.

In the year, 2009 production of gypsum started in Angola by Fabrica de gesso do Sumbe. Other companies are also interested in mining the minerals, such as a well-known mining company in Ireland, Aurum Exploration Services, which has started exploring high-quality gypsum in Angola. The project was carried out with the help of one German company and two Angolan companies. According to the estimation of USGS, in 2011, Angola's gypsum production was 200000 Tons. Cuba imported gypsum, anhydrite, and plasters of gypsum from Angola for up to the U.S. $ 165 in 2018.[5]

Fig.2: Selenite (Baia dos Tigres , Tombwa , Angola) [from https://www.mindat.org/loc-107922.html]

Fig.3: Location of Tigers Bay on map [from https://www.mindat.org/loc-107922.html]

2.1.3 Industrial sources

There are many processes in industries that produce gypsum, a by-product, such as citric acid and phosphoric acid manufacturing. Smokestacks produced due to the burning of coal and other materials are a source of gypsum by removing waste gases. It can also be produced by the process of desulphurization of flue gas. In the USA, 20 million tons of flue gas desulphurization residues are produced annually. This material consists of a high amount of calcium sulphate dihydrate.

Using rock phosphate, phosphoric acid is produced. In this process, gypsum is obtained as a co-product. This is produced from the neutralization of waste sulphuric acid by limestone or lime in production. Generally, it is pure gypsum with a few traces of other elements. Titano gypsum is obtained as a by-product during the production of titanium dioxide. Boro gypsum is obtained during the manufacturing of boron-containing compounds. fluoric gypsum is obtained as a by-product during the production of hydrofluoric acid using feldspars.

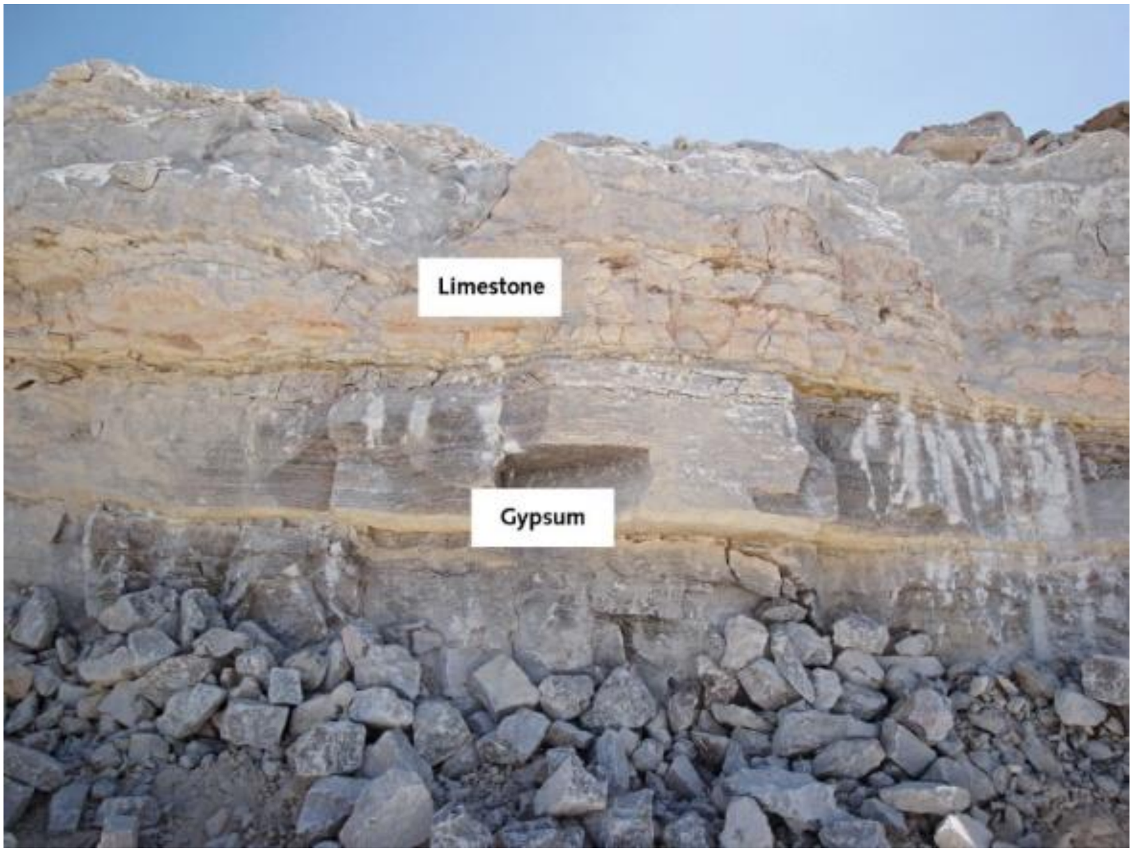


Fig.4: Natural Sources of Gypsum [from: https://www.zkg.de/en/artikel/zkg_2012-07_India_Gypsum_demand_and_supply_1447234.html]

However, the regular presence of black impurities produces a rock of various shades of grey, brown, and even black.

2.2 Production of gypsum

Thermal dehydration is used to create gypsum from natural or synthesised dihydrates of calcium sulphate. This is known as calcination, and the formula carries it out:

$CaSO_4 \cdot 2\ H_2O + heat \rightarrow CaSO_4 \cdot 0{,}5\ H_2O + 1{,}5H_2O$

There is generated from the initial raw material binders, which significantly differ in their characteristics according to the heat processing techniques (Table l). The two most common forms of binders formed during calcination are α-gypsum and β-gypsum. While β-gypsum is produced by simply heating natural gypsum at room temperature, a-gypsum is produced by heating in an autoclave while simultaneously raising pressure with saturated water vapour. Both forms of gypsum (α and β) are calcium sulphate hemihydrates. They have the same chemical formula but differ in their degree of aggregation (the size of crystals and the degree of aggregation). Because of the frequency of crystal-lattice faults, their technical capabilities vary significantly (Table 2). a-hemihydrate is typically regarded as a higher-quality binder. It features more compact, regular needle-like particles and a better structured crystalline lattice, which results in a higher strength once the paste hardens. [6]

The particles of β-hemihydrate are porous and irregular in form. Because β-hemihydrate has a higher frequency of flaws in a crystalline lattice, it has a larger specific surface than α hemihydrate even with the same granularity and hence a greater need for batch water. As a result, the hardened β-gypsum has reduced strength. Natural gypsum, synthetic dihydrate, and gypsum shards can all be used as raw materials in the manufacturing of gypsum (e.g., from ceramic forms). Production begins with a natural material that has been handled, cleaned of contaminants, crushed, and sorted into various sizes. Thermal processing of the processed raw material can be accomplished using digesters, autoclaves, and rotary furnaces. The ground calcined gypsum is subsequently processed to the desired fineness. [6]

It is preferable for manufacturing to have as much dihydrate as feasible in the original raw material. The presence of anhydrite (anhydrous calcium sulphate) might jeopardise a manufacturing process and perhaps the product's quality. The formation of more anhydrite during the gypsum manufacturing process is also undesirable. This can occur because of a more significant temperature caused by negligent calcination. [6]

Tab.1: scheme of the dehydration of the calcium sulphate dihydrate and forms of the $CaSO_4$ [6]

<table>
<tr><td colspan="2">$CaSO_42H_2O$
Dihydrate (DH)
↓
150ºC</td></tr>
<tr><td>α – $CaSO_4.0,5H_2O$

α -hemihydrate (α -PH)
under high pressure in a
saturated water atmosphere
(autoclave)
↓
200-210ºC
α -$CaSO_4$
α – anhydrite (α - AIII)</td><td>β – $CaSO_4.0,5H_2O$

β -hemihydrate (β -PH)
under high pressure in a
saturated water
atmosphere (autoclave)
↓
170-180ºC
α -$CaSO_4$
β– anhydrite (β - AIII)</td></tr>
<tr><td colspan="2">Over 200ºC
$CaSO_4$ II
Anhydrite II (AII-T,AII-N,AII-E)
↓
0VER 800ºC
$CaSO_4$ I
Anhydrite I (AI)</td></tr>
</table>

Tab.2: Differences between α and β hemihydrate [6]

Types of gypsum	α - hemihydrate	β - hemihydrate
Particle size	small (10-20mm)	tiny (1-5 mm)
Porosity of particles	low	porous
Specific surface	small	high
Crystal lattice defects	small	large
Strength increase	slower	faster
Final strength	higher	lower

2.2.1 Production process of gypsum

The production process is separated into five stages: crushing, screening, grinding, calcination, storage, and transportation. [7]

1. Crushing: The mined gypsum ore raw material enters the crusher through a vibrating feeder, and the crusher break the large-size gypsum ore into small particles

2. Screening: Use a vibrating screen to separate incomplete massive particles and impurities combined in beaten gypsum.

3. Grinding: The sieved gypsum is fed into the grinding mill in a uniform and constant way through vibrating feeders for grinding.

4. Calcination: Calcination typically uses direct contact between the hot high-temperature flue gas from the boiling oven and gypsum raw materials to complete the calcination and dehydration of gypsum powder.

5. Storage transport: Qualified calcined gypsum powder is despatched to the clinker warehouse for storage or to the workshop to produce gypsum board, cement, and other gypsum products.

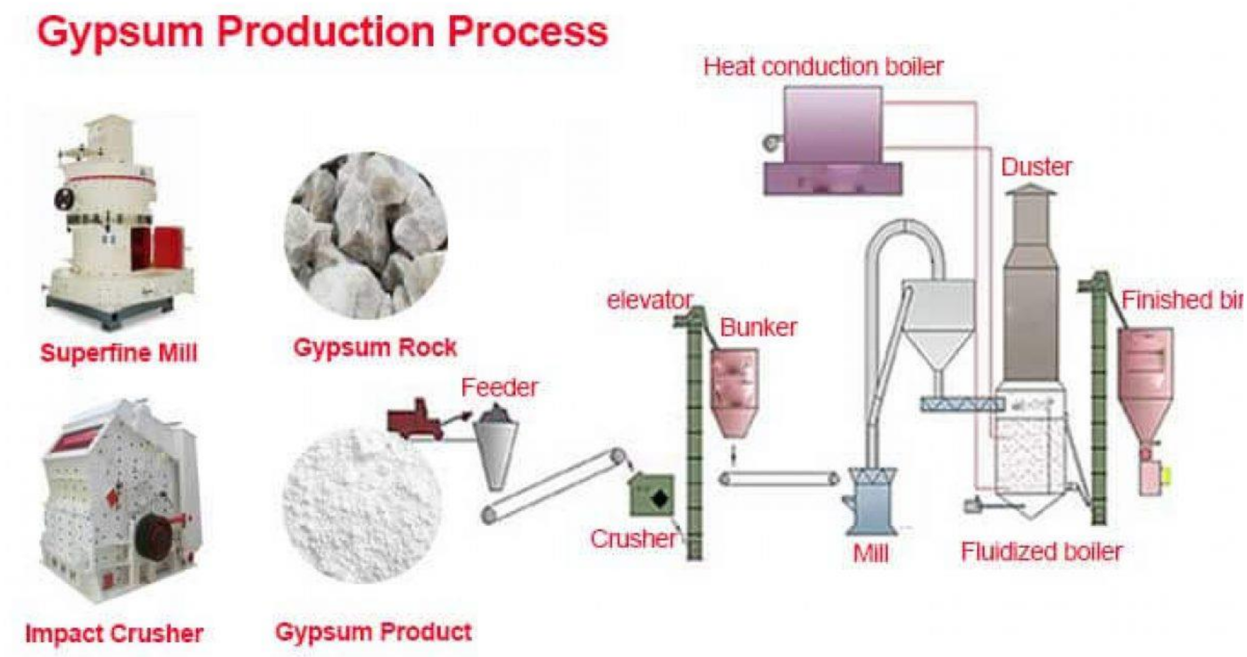


Fig.5: gypsum production process [7]

2.3 History

In the age of 3700 B.C, during the construction of the pyramids of Cheops, Egyptians used gypsum blocks and plaster. In 1200 B.C, King Minos of Crete's constructed his palace using gypsum. In 1760, 's gypsum was being mined in Paris, and new building material was introduced as Plaster in Paris. In 1792 large gypsum beds were discovered in New York, and within 100 years, gypsum mines were opened at several locations. In 1880 two Americans named Augustine Sacket and Fred Kane first used gypsum to prepare wallboards that consisted of gypsum plaster pressed between four layers of wool felt paper [8]. Gypsum is primarily on sedimentary rocks, utilized to prepare Paris concrete and fertilizer used in the construction industry. Critical components in many types of concrete, chalkboard, and wallboard. General information about gypsum is that it belongs to the Sulphate minerals group.

Fig.6: History of gypsum in summarize form [from: https://faculty.uml.edu//nelson_eby/89.307/material.htm]

2.4 Properties

Gypsum binders can be classified in various ways, including their intended purpose, manufacturing technique, and technical features.

Gypsum binders are classified according to their use as building gypsum (from which building units, plasters, stucco products, and gypsum drywall are produced), technical gypsum, which is used not only in the building industry (e.g. modelling gypsum in the ceramic industry serves in the production of gypsum forms), and modified gypsum into which admixtures for improving workability, adhesiveness, composite gypsum binders (gypsum with the addition of additional binders) form a distinct category.

The standard SN 72 2301 specifies the approved varieties of gypsum for various applications. According to this standard, individual types of construction gypsum are labelled based on the grinding fineness and the setting period (Tab.3). They are then ranked by suitable class of strength based on compression strength. [6]

Tab.3: Types of gypsum according to the fineness of grinding and the setting time

Type	Mark	Initial setting time	Final setting time max
quick – setting	A	2 min	15 min
normal – setting	B	6 min	30 min
slow – setting	C	20 min	not given

Tab.4: Type of gypsum according to particle size

Type	Mark	Retained on sieve 0,2 mm max. in %
coarse grinded	I	30
middle grinded	II	15
finely grinded	III	2

2.4.1 Physical properties of gypsum

It varies from colorless to white. It can be yellow, blue, pink, brown, grey, or reddish due to the presence of impurities in it. It generally has a prismatic crystal habit but can also be found in the form of flat and elongated crystals. It exists in both inflexible and inelastic Forms. According to the Mohs scale, its hardness lies between 1.5 and 2. Its surface condition varies from silky to vitreous, perky, or waxy. It has a white streak. Diaphaneity of gypsum is transparent to translucent. The specific gravity of gypsum varies between 2.31 and 2.33. It has biaxial property in optics. It is relatively soluble in water. The solubility of gypsum in water depends upon the temperature of the water. Gypsum has a different scenario than other salts, with the; ease in temperature solubility of gypsum decreasing. This property of gypsum is known as retrograde solubility. Sometimes crystals of gypsum are found in pearls of the flower. This form of crystal is known as a desert rose. The name is due to the presence of crystals on gypsum crystals terrains.

Fig.7: Physical properties of gypsum in summarize form [from https://faculty.uml.edu//nelson_eby/89.307/material.htm]

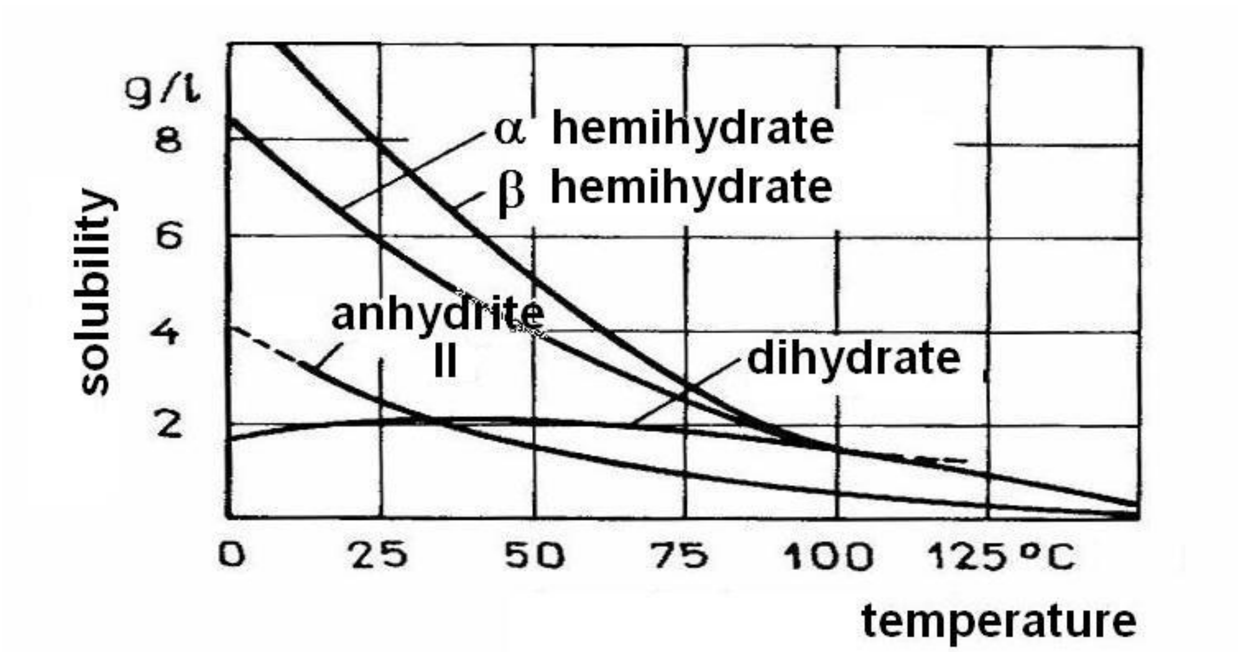


Fig.8: Solubility of some types of calcium sulphate in the water [6]

2.4.2 Chemical properties of gypsum

This property of gypsum includes chemical classification and chemical composition of gypsum. It is classified as sulfate minerals when it's a raw material it's called dehydrate ($CaSO_4.2H_2O$).

When its calcinated to be used its sulphate hemihydrate ($CaSO_4.0,5H_2O$), when mix with water (H_2O), calcium sulphate dihydrate is made again.

$CaSO_4.0,5H_2O + H_2O \rightarrow CaSO_4.2H_2O$

2.4.3 Mechanical properties of gypsum

The compression strength of gypsum is the most important mechanical property to examine. It varies from 2 to 25 MPa depending on the grade (class of strength) of the gypsum. Hardened gypsum has an elasticity module ranging from 2000 to 6000. MPa, with a compressive-bending strength ratio of approximately 3:1. A variety of factors influence the mechanical characteristics of gypsum. Its wetness has the greatest impact. The dried tenacity of the strength of gypsum is 2 to 3 times that of a damp substance. Even little variations in moisture have a big impact on mechanical performance properties. A change in the moisture of 0.1% of the mass can induce changes in strength up to 8%. Because gypsum is very hygroscopic, its strength is determined by the moisture content of the environment in which it is located (Table 5).[6]

Tab.5: Influence of the gypsum moisture on the strength [6]

Curing of gypsum	Gypsum moisture	Compressive strength	
		MPa	%
drying at 35 - 40 ° C	0	13.8	100
air humidity 65 %	0.04	13.6	98.5
air humidity 90 %	0.15	12.9	93.5
full saturation by water	17.5	6.4	46.5

Defects caused by moisture are caused by the inappropriate incorporation of gypsum products. This occurs when the moisture content of a gypsum product is exceeded, and the product is installed without drying out, or when a still improperly dry gypsum surface is faced.

Building blocks made of gypsum can be used in environments where relative humidity does not exceed 75%, but at greater humidity levels, proper precautions must be taken. However, it has been observed that in a typical living space setting, any variations in strength are not a major issue, especially because gypsum may regain its previous strength after drying down.

Tab.6: Influence of water-cement ratio on the strength [6]

w/c	slow-setting gypsum		quick-setting gypsum
	Bulk density	Compressive strength *	Compressive strength *
	$kg.m^{-3}$	MPa	MPa
0.50	1410	14.6	15.8
0.55	1300	13.0	14.0
0.60	1230	11.4	12.0
0.65	1170	10.8	
0.75	1040	9.5	
* After 13 days in room temperature + 1 day in 50 °C			

In the presence of appropriate workability, the dependence of compression strength on the water-cement ratio follows a hyperbolic path.

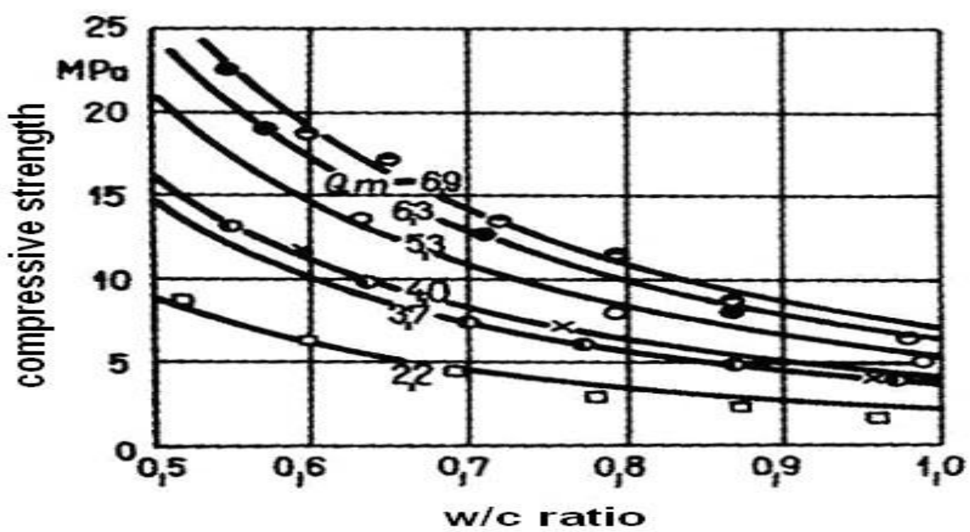


Fig.9: Influence of water-cement ratio on the compressive strength for different types of gypsum [6]

2.4.4 Fire resistance properties of gypsum

Gypsum is one of the most widely used building materials, especially in interior construction. Gypsum is used as additional material. Used primarily in the construction of walls and roofs. It is also a pre-made unit, such as a gypsum board purchased during installation. It can withstand fire. They stop the spread of fire to ensure the safety of life. This gypsum resistance to fire is due to the presence of water within the gypsum products. For example, 15mm thick gypsum plasterboard has about 3 liters of crystal-clear water. Evaporation causes a protective layer covering the gypsum product when a fire approaches the water. This will help prevent fire from spreading to other things. Gypsum is around 21% chemically treated water by weight, which significantly impacts its fire resistance. Water is slowly released as steam when gypsum drywall is exposed to fire, thus preventing heat transfer. Gypsum drywall is fire-resistant due to the addition of glass fiber reinforcement and other additions to its specifically made gypsum framework, which helps it resist fire impact. Fire safety legislation, which aims to reduce fire-related risks, has a significant effect on the overall design of buildings in terms of structure, aesthetics, functionality, and cost. Historically, building fire safety has been regulated using codes and "prescribed" standards; however, instruction codes have become more complex, showing little or no flexibility in solving new solutions and cost-effective designs. Gypsum plasterboards are an aesthetically pleasing, easy-to-use, and durable material for machine walls, floors, and ceilings, displaying good heating and fire protection features. When gypsum is subjected to high temperatures, water molecules bound to the crystal lattice are released and transferred in bulk; this process of "gypsum dehydration" is very endothermic, thus improving the fire resistance of the whole structure. This process is known as dehydration of gypsum. This phenomenon occurs in-between temperatures of 80 and 250 C^{o}. The chemical decomposition of gypsum occurs in two stages. In the first stage, 75% of the water of sulphur di-hydrate is lost. Calcium sulfate hemihydrate is the result of this phenomenon. In the second stage, if gypsum is again heated, the second reaction occurs in which calcium sulfate hemihydrate loses its remaining water. Both reactions are highly endothermic; as a result, heat transfer by G.P. is blocked until the G.D. process is complete. The final products of the G.D. process are calcium sulfate anhydrite and water vapour; the latter spreads to the gypsum's pore network and is finally removed from the G.P. area. There are two critical macroscopic effects due to dehydration of gypsum. Effect on thermophysical properties, e.g., specific heat, thermal conductivity, density occurs. Another effect of dehydration is the production of water vapours through mass diffusion released from the surface of the gypsum plasterboard.[9]

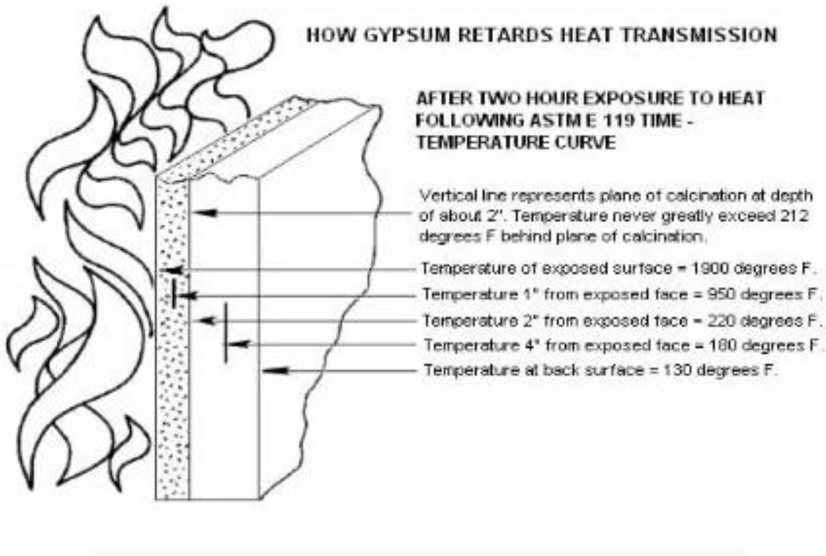


Fig.10: Gypsum heat retarding property [from:https://theconstructor.org/building/gypsum-products-properties-building-construction/14949/]

2.4.5 Water resistance properties of gypsum

A small amount of siloxane is often added to an aqueous slurry used to produce a gypsum-based product, formed and dried. However, it has been observed that the siloxane needed to manufacture a water-resistant gypsum-based product is fully curable and incurable in some situations. Water resistance does not develop to a suitable level in any scenario. [10]

2.5 General use of gypsum

Gypsum is used:

- In the manufacturing of cement and wallboard.
- In dentistry for toothpaste, mould for dentures [11]
- In medicine for various products, e.g., arm casts
- In winemaking industries to control wine tartness [12]
- In food additives, as a source of calcium
- In the agriculture field, as an additive for the improvement of soil fertiliser

3.0 Gypsum with natural fillers

Gypsum is widely used as an insulation material in the construction industry due to its unique thermal property and its eco-friendly material. Natural fibers are being used in gypsum insulating material at a different percentage. These natural fibers include fibbers of date palm, wood wool, cork fibers, rice husk, wood sawdust, bamboo fibbers, etc.

3.0.1 Types of fibbers used in gypsum

Gypsum-based composites are mainly used for interior design due to their durability, fire-resistant property, and low prices. Production of gypsum composites naturally and from industry shows that gypsum by-products are very famous nowadays. But the disadvantage of this product is their brittleness and low water resistance. This disadvantage limits the use of gypsum composites. Many studies have been done to use fibbers to improve the performance of gypsum composites. Gypsum composites reinforced with fibbers show good performance.

Following are some types of fibbers [13]:

Mineral fibbers

Mineral fibbers include 1.5 % basalt.

Wood fibbers

Wood fibbers include 1.5 % cork.

Stalk fibbers

Stalk fibbers include 2.9 % straw and 1.5 % cotton.

Fruit fibbers

Fruit fibbers include coir 4.4 % and palm 2.9 %.

Bast fibbers

Bast fibbers include jute 1.5 % and hemp 4.4 %.

Leaf fibbers

Leaf fibbers include sisal 8.9 % and abaca 1.5 %.

Recycled fibbers

Recycled fibbers include packaging kraft 1.5 %, sawdust 2.9 %, paper 1.5%, tyer 1.5%, textile 1.5 %, and tobacco 1.5%.

Organic fibbers

Organic fibbers include polyamid (PA, 7.4%), polypropylene (PP, 11.8%), Polyacrylonitrile (PAN, 1.5%), Polyvinyl alcohol (PVA, 4.4%), and polyperaphenylene terephthalamide (PPTA, 1.5%)

Inorganic fibbers

Inorganic fibbers include aluminium 1.5 %, carbon 1.5 %, and glass 25%.8 [14]

3.1 Comparison of types of fibbers in summarize form

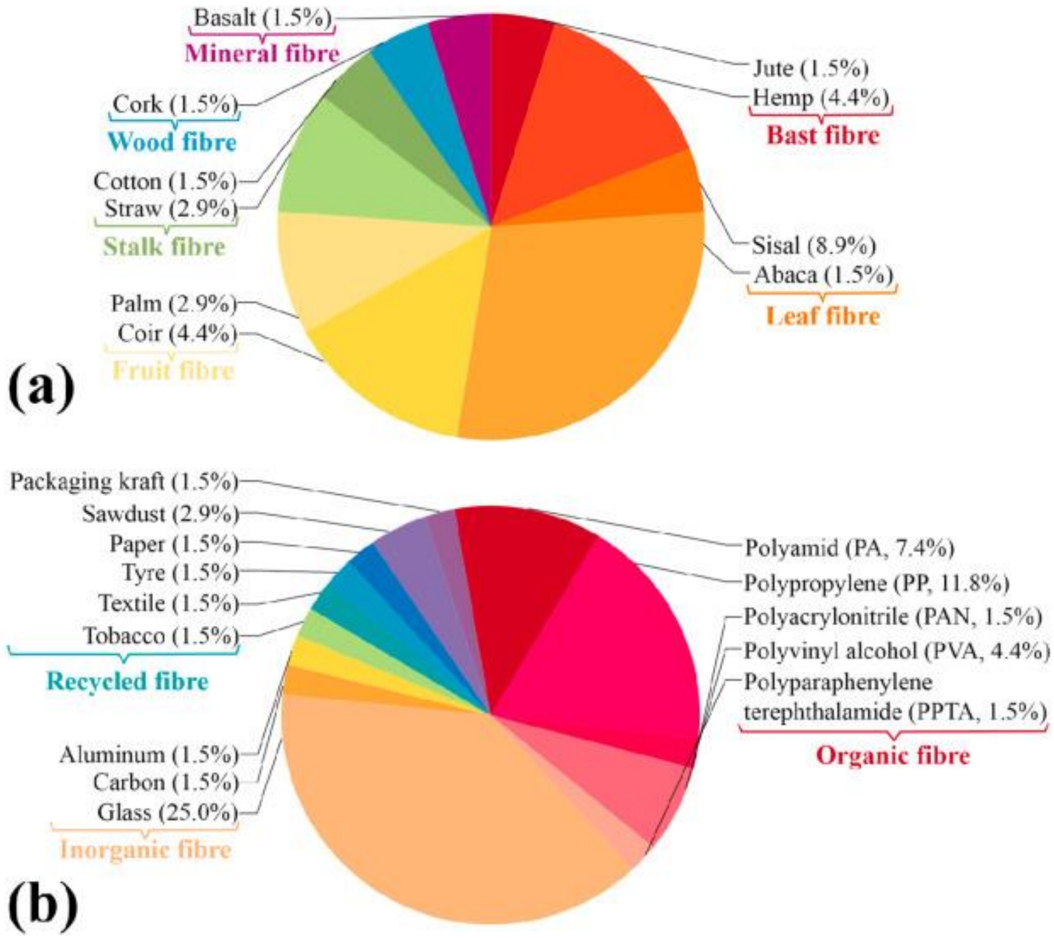


Fig.11: Comparison of types of fibbers form [13]

3.2 Wood waste

Wood is an important raw material for construction, and materials are becoming increasingly in demand as a renewable resource. Furthermore, changing consumer habits result in the production of ever-increasing volumes of waste wood, which can be used as a feedstock for the cascade manufacture of new materials like particleboard. Current legislation and wood waste recycling methods, on the other hand, need to be improved to maximize the volumes that can be reused and improve the qualities of recovered wood. The present French and European legislation and the innovations under development in this field are described in this review [15]:

- Innovative automated sorting systems
- Physical-chemical processes for cleaning leftover glue from the surface of wood particles

- Cleaning of wood waste

Wood waste mainly concentrates at processing plants, such as plywood mills and sawmills. The amount of waste generated by wood processing industries varies according to the type of raw material and finished product utilized [16].

Fig.12: Wood waste types [16]

3.2.1 Types of wood waste

Following are some types of wood waste [17]

I. **Natural untreated wood waste**
Natural wood includes sawdust and debris from forest management and residual wood from sawmills.

II. **Scrap wood waste**
Scrap wood is untreated wood offcuts from construction sites, as well as production waste from sawmills, carpenters' workshops, or furniture factories (scaffolding planks, struts).

III. **Used wood waste**
Wooden building components and supplies, such as wooden packing (crates, palettes), as well as wooden furniture, are all examples of used wood.

IV. **Problem wood waste**
Wood treated with wood preservation chemicals, laminated wood waste, and mixes of problem wood waste and other wood are all examples of problem wood waste.

3.2.2 Uses of wood waste

Wood waste is a type of waste that contains discarded wood products, whole trees, stumps, and trim branches generated during street and park maintenance. Used timber, small shipping pallets, trees, components, and other wood debris from building and demolition are the primary constituent of wood waste. Many specialists discuss about various ways to reuse this valuable resource. The diameter of the logs being processed, the type of saw used, the product specification required, and the workers' skills influence the waste generated by wood processing. Every day, sawdust, offcuts, trims, and shavings on waste products from wood industries such as saw millings, plywood, veneer, and others. Sawdust is produced during the cutting, sizing, re-sawing, and edging of wood, whereas trims and shaving made used during the trimming and smoothing of wood. When 1,000 kilos of wood are processed in the furniture industry, about half (45%) of the wood is wasted, resulting in 450 kilos of waste.

Four to six million tons of timber enter the waste stream each year because of the unstable economy. Most of it comes from two sources: building, demolition, and renovation debris, as well as packaging (such as pallets) used to carry goods. Therefore, the vast bulk of wood waste is produced. Similarly, while processing 1,000 kilos of wood in a sawmill, the waste will be more than half (52%) of the total weight, resulting in 520 kilos of wood [18].

It's never clear how we'll use the scrap wood and residues. We talked about some of the different ways people use it throughout the world.

Bark

The wood processing industry is coping with the issue of what to do with barks. The complexity of bark and the great variety in chemical and physical qualities of barks of different wood species are required for optimal usage of bark residues. Surplus bark is the most confusing residue issue currently affecting the wood-conservation industry. Bark has valuable products that are awaiting the correct economic conditions or the development of suitable commercial uses. Efficient bark usage can generate a new drive and help the economy by turning a costly waste into a profitable asset. Bark can be used to make the following items.

Tab.7: materials originated from bark [19]

1. Fibbers	2. Cork
3. Tannins	4. Resins
5. Gums	6. Dyes
7. Latex Material	8. Flavours
9. Fish Poisons	10. Antibiotics
11. Medicines	12. Arrow poisons

Charcoal:

The popularity of charcoal for recreational purposes has risen. The raw material for this charcoal includes bark from mechanical de-barkers and slab wood with a high bark percentage. The presence of ash in the bark is commonly assumed. This isn't always the case. The ash content of clean bark is just slightly higher than that of wood. Bark charcoal is easier to crumble and includes a higher percentage of particles than wood charcoal.

Wood-based Materials:

Building insulation boards, hardboards, fibreboards, and particleboards are all products in which bark can be found. Almost every style of the board had different barks added to it. Because bark transfers heat more slowly than wood, its use as an insulating board appears to be particularly desirable. Furthermore, many softwood barks include a high concentration of resins and waxes, which can eliminate the requirement for sizing. Indeed, bark's higher extractive content could help bind the particles together.

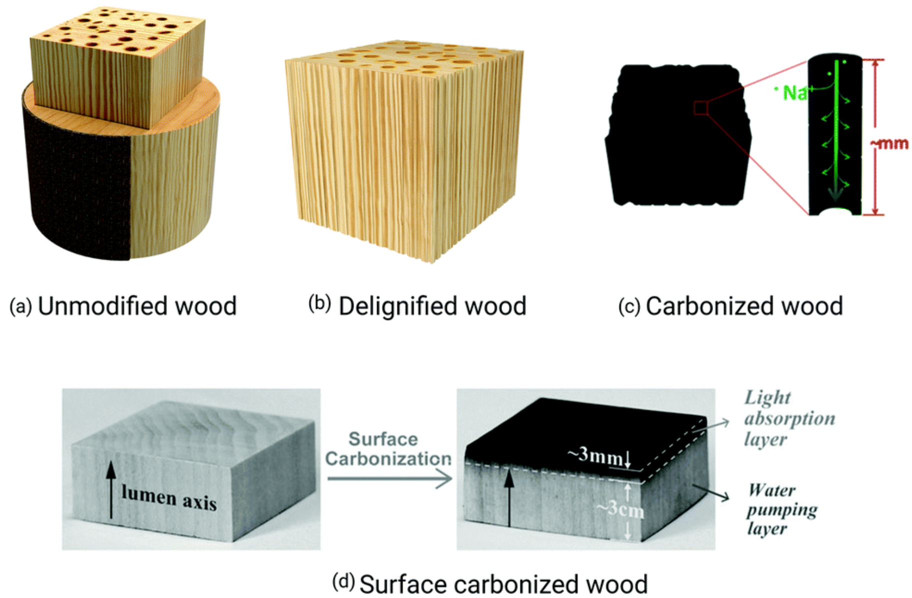


Fig.13: Wood-based materials [20]

Sawdust and Shavings:

The cost-effective disposal of sawdust and shavings is a rising challenge for the wood industry. Sawmills produce massive amounts of sawdust every year.

Following is a summary of the use of sawdust and shavings:

- Uses of the material mentioned above due to unique physical qualities. Sawdust and shavings are utilised as fillers in composites; in mouldings, they provide low-cost impact resistance, shrinkage control, and good electrical insulating features, as for insulation, non-conductive
- Use as fuel: this is roughly half of the heat produced by fuel oil and three-quarters of the heat generated by mineral coal. Sawdust and shavings have become increasingly popular in the production of charcoal briquettes in recent years.
- Use as wood-base board and fibber: Engineered wood products Engineered wood is used to describe a product composed of smaller bits of wood that have been joined together with glues, resins, and other chemicals to create a wood-like product. Oriented strand board, particleboard, glued-laminated timber, laminated lumber, wood I-joists, and finger-jointed studs are all examples of engineered wood.

Sawdust Shavings I Shavings II Pellets

Fig.14: Sawdust and shavings [21]

Urban wood waste recycling:

Wood wastes produced at residential and commercial wood frame construction sites have a more significant potential for reuse. Trim and pieces produced during framing and trimming area generally clean and uniform waste stream that can be used to make engineered wood. Processors are keen to get this type of wood waste since it represents a very valuable source of recyclable material. Because of its non-uniform character, demolition atypically normally produce a significantly less desired type of wood waste, which is enhanced by combining the wood with other components. The wood can still be used, although it is usually of low value and is intended for boiler fuel or mulch feedstock. Because demolition generates significantly more waste per square foot than construction, disposal costs account for a much larger portion of operational costs.

Lumber:

The reuse of structural or architectural components, such as casings, banisters, and moulding, is the desired option for wood waste management. Massive timbers from older or one-of-a-kind structures can be preserved and used as structural elements in new construction. A timber grading inspector must re-certify lumber that is utilized as a structural element.

Fig.15: Reclaimed lumber [from http://yr-architecture.com/reclaimed-timber-benefits-and-challenges/]

Mulch or compost feedstock:

Mulches made of chipped wood and bark are popular. Wood is a good bulking ingredient for composting, although it usually requires the addition of a nitrogen source. [19]

3.3 Properties of gypsum with fibbers

Researchers analysed natural and synthetic fibbers to improve the mechanical behaviour of the novel composites. Fibbers have traditionally been used to strengthen low-quality materials like compacted earth or clay, improving cohesion and mechanical strength. Fibbers being used for reinforcement are in Table 8.

Tab.8: Fib**b**ers used for reinforcement [22]

Natural Fibres			**Synthetic Fibres**	
Palm Fibres	Straw	Sisal	Glass fibbers	Polypropylene (P.P.) fibbers
Wool	Esparto	Palm Fibres	Steel fibbers	fibbers
Cane	Jute	Oak Fibres	Polyester (PET) fibbers	Nylon fibbers

Hemp	Bamboo	Husk		

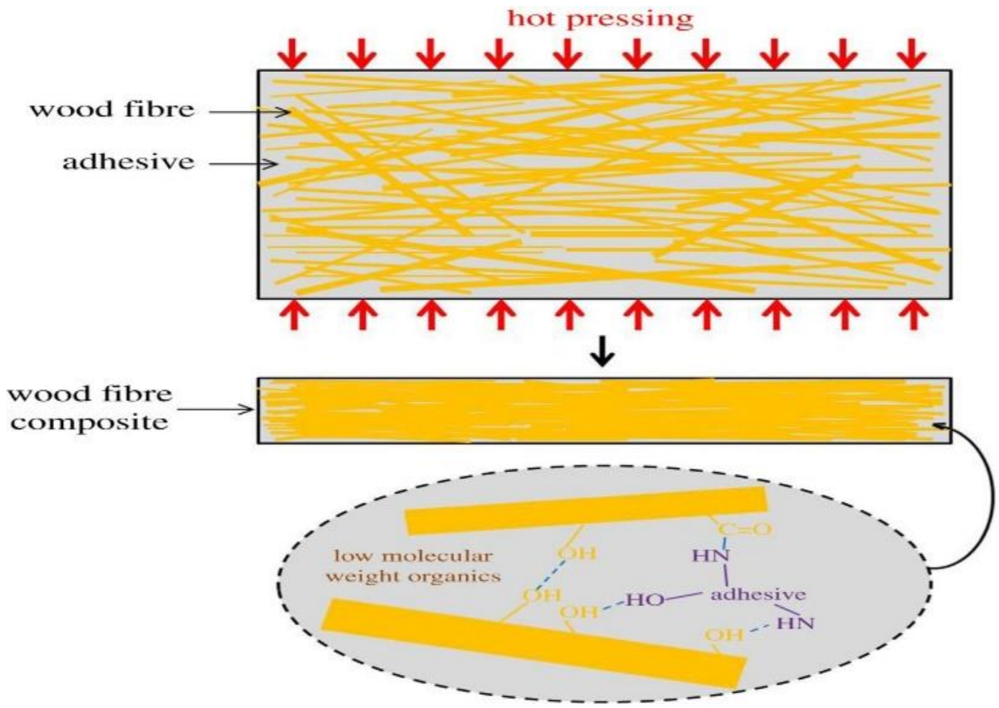


Fig.16: Wood fibber composite [23]

Several researchers have explored blending fibbers into gypsum-based composite materials. Hernandez Olivares et al. [24] used sisal fibbers at various lengths and percentages in their research. The results showed that adding 1% of 2 cm long sisal fibber increased compressive strength when compared to the reference material. Sisal fibbers with a length of 3.5 cm and a flexion resistance of 3 per cent excelled in the reference material. The best results for the elasticity modulus were obtained by adding 1% fibre with a length of 4 cm. Oteiza-San José [25] investigated the behaviour of sisal-reinforced plaster by applying it to low-cost housing items, whereas Garcia Santos [26] investigated the reinforcing effect of natural Typha Latifolia fibbers on plaster construction applications. This form of the fibber reduces the weight of the compounds by up to 23.06% and improves their flexural tensile strength, but not their compression resistance. [22]

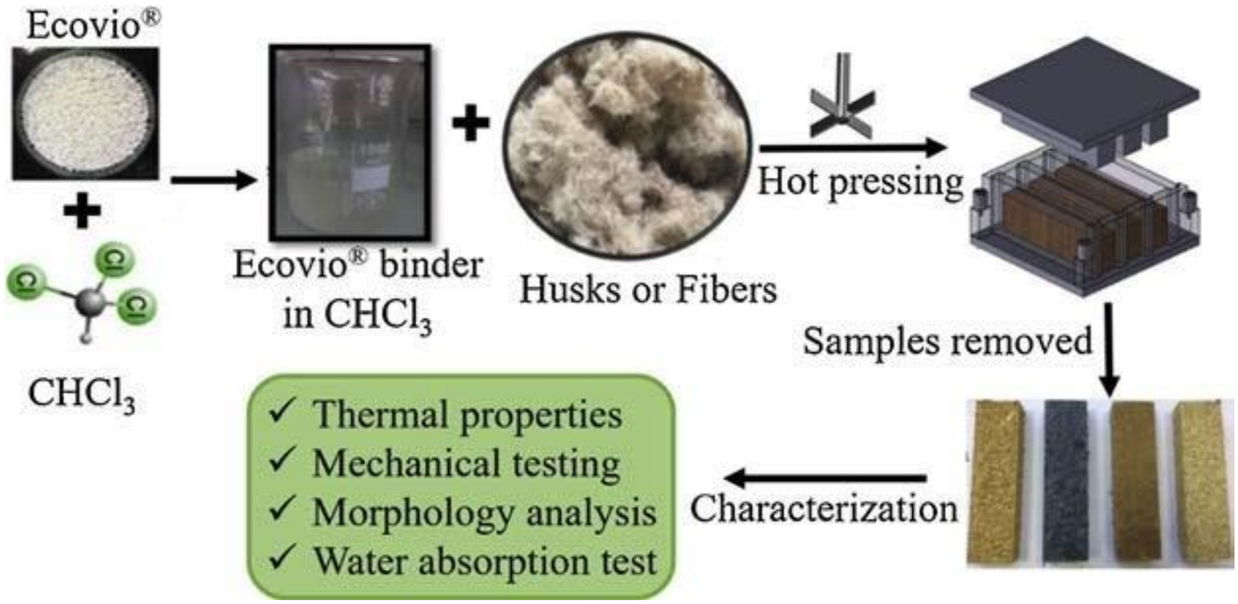


Fig. 17: Composites processing steps [30]

Glass fibre is the principal reinforcement material in gypsum or plaster-based goods, and synthetic fibbers or minerals have been widely studied. Del Ro-Merino et al. [27] discovered that including fibber into gypsum and plaster matrices enhances resistivity. Based on their findings, the scientists recommended early formation uses, such as self-supporting partitions made from these materials. Romaniega-Pieiro et al. [28] explored the use of mineral wool fibres from recycled CDW to reinforce plaster, and their results indicate that rock wool and glass wool from CDW can be used instead of traditional glass fibre reinforcement to enhance the bending, compression, and hardness of the Shore C surface. Serna et al. [29] employed up to 5% weight of gum particles from used tires in the gypsum matrix. Compared to the reference material, flexibility was reduced up to 16 percent and compressive strength losses of 18.3% resulted.

Frayed textile fibbers could be reused in gypsum-cork compounds, according to Vasconcelos et al. [30]. They could mitigate the material's loss of compressive strength by adding cork aggregate while also raising the ratio of textile fibbers needed in the process.

The research examines the physic mechanical properties of gypsum-based composites and wood from demolition debris after adding natural (straw) and synthetic (glass fibre) fibres to determine the impact of these changes.

Adding fibres to gypsum-wood composites makes them lighter, while using straw as reinforcement makes them lighter. Adding wood waste in the form of shavings and sawdust reduces the density of the composites when compared to the reference gypsum. Water absorption by capillarity increases as the quantity of wood waste added additions; absorption is higher in mixtures containing wood shavings than in sawdust at the same percentage. On the other hand, the thermal behaviour of the new materials differs in those mixtures with more wood shavings that have a lower thermal conduction ratio.

According to Rodríguez-Liñán et al. [22] adding glass fibre as reinforcement to gypsum-wood blends improves the material's flexural strength This increase gets more significant as the percentage of fibre used rises. Prepared composites were lighter and more resistant to flexural strength than the reference material by using up to 20% wood waste. The compound with 5% of saw dust and 2.5% of glass fibbers have the most significant rise, increasing 81.25% over the standard value. The use of straw as a flexural strength reinforcement, on the other hand, did not result in a considerable improvement. Apart from inflexion, adding glass fibbers to the gypsum-wood composites increases their ability to sustain compressive stresses, but it does not significantly exceed the values for the reference material. SEM analysis of straw shows that it causes a significant breakdown in the gypsum matrix, which explains why this type of reinforcement has a lower strength.

Fibbers are added into composite materials based on plaster to increase their tensile help in lowering their fragility. The important premise is that such fibbers can prevent cracks from growing and propagating. A good bonding between the fibber and the matrix, a uniform distribution of fibbers, and a low number of voids are the key parameters for the perfect mechanical strength of fibber-reinforced composites. When natural fibbers are added as a reinforcement of the plaster, the total resistance to bending varies significantly. The ability of a sandwich panel of plaster destroyed to 66 percent and reinforced with a 5 cm long sisal fibber. The panels showed good resistance after 28 days of exposure to moisture, holding in the water without being eroded, whereas the non-reinforced plaster begins to erode on the third day of soaking. In a study of the resistance to screwing of gypsum board reinforced with wood fibbers, Pascal Boustingorry [31]. The reinforced mortar of wood fibber changes in response to the stimulus in bowing than the mortar that is not strengthened. The presence of wood fibber provides a significant barrier to the crack's spread. Bederina et al. [32] studied the impacts of wood chips on the thermal characteristics of sand concrete and found that adding wood chips lowers the density of the material while enhancing its conductivity. The reinforced plate is more resistant to screw movement than the non-reinforced plate. Taoukil et al. [33] investigated the thermal insulation capacity of this type of material and found that adding wood wool into cement sand reduces the thermal conductivity and density significantly. On the other hand, they discovered that the water content percentage significantly impacts the heat conductivity of mortar reinforced with wood wool. Barreca et al. [34] studies show adding 70% of the dry olive stone value to cement mortar reduces its heat transfer, resulting in improved thermophysical properties that allow it to be used as a building component. The use of natural fibber from cement cardboard packing to reinforce plaster was studied, and it was found that the fibbers joined well to the matrix network, increasing mechanical resistance. The plaster plate strengthened with used paper is strong and durable and fire-resistant. Other research has been done on using date palm fibbers as a reinforcement ingredient in plaster matrix [35]. After many tests, they've come up with the perfect mixture for a plaster mortar reinforced with date palm fibbers that fulfil all the mechanical and physical criteria for a building material. The observed findings demonstrated a total change in the material's rheological behaviour, as well as a significant rise in its bending resistance and flexibility, as well as an enhancement in its cracking limit. The thermal conductivity of vegetable fibbers reduces as the mass rate of the fibbers increases, according to the authors.

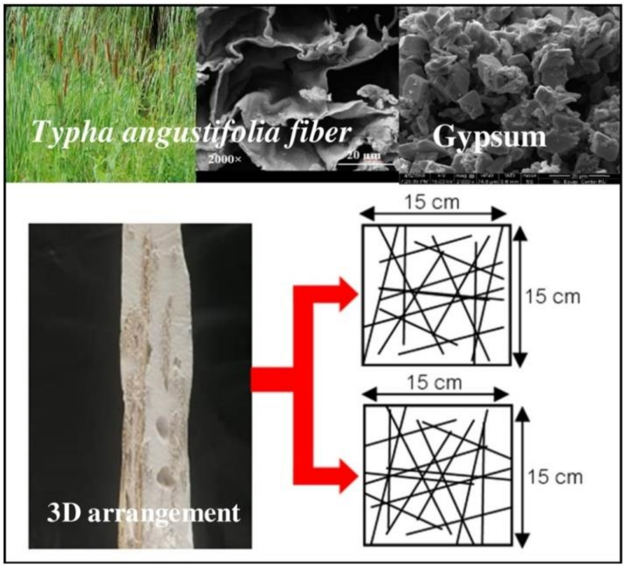


Fig.18: Use of typha angustifolia fibber in gypsum[36])

A biobased resin, a poly (butylene adipate) blend, was used by Muthuraj et al. [37] to bind agricultural waste (such as cereal husks) and textile waste for compound insulation panel applications. Even though the efficiency of the produced composites in real life needs to be studied, the results obtained suggest that a new class of sustainable materials for building interior insulation applications could be developed. Rice husks, with a density of 378 kg/ m^3 and a lower water absorption, had the best insulating value (0.08 W/m. K) among the produced bio composites (40 percent after 24 h immersion in water). All the bio composites were semi-rigid, with adequate flexural (0.80–2.25 MPa) and compressive (10–40 MPa) properties. By replacing traditional building materials with the created bio composites, the environmental effect will be reduced. To improve bio composite processing at the industrial level, more research should be done.

4 Experimental part

4.1 Aim of the work

The aim of this work is to explore the union of gypsum and wood waste fillers and determine the most viable combination of both materials by investigating of the main wood-gypsum material properties. By that the economically affordable and environmentally friendly material suitable also for the less developed countries will be designed.

The investigated parameters are:

- Basic physical properties
- Thermal properties
- Water vapor transport parameters
- Mechanical parameters

4.2 Objectives

• All data collected will be measured on specimen sets properly prepared for this purpose. To achieve a significantly wide diversity of material qualities, four unique combinations will be mixed.

• Measured values will be compared to data from past experiments, followed by a discussion of the experiment's success.

• The resultant proposed combination will then be derived based on the above-mentioned facts

4.3 Materials

Commercial FGD gypsum plaster (producer Rigips, Czech Republic) was used as a binder in all designed composites. The chemical and mineral composition were determined by XRF and XRD analysis and the results are in Tab. 9 and 10. The results of XRD analysis can be seen in Fig. 19. The calcined gypsum powder contained 82% of calcium sulphate hemihydrate (bassanite, $CaSO_4 \cdot 1/2H_2O$). Also, some amount of anhydrite ($CaSO_4$) and dihydrate (gypsum, $CaSO_4 \cdot 2H_2O$) was found. The hydrotalcite originated from the fly ash, because the gypsum plaster was prepared from glue gas desulfurization (FGD) gypsum.

Tab.9: Chemical composition of gypsum

Element	Amount [%]
Calcium (Ca)	58.21

Sulfur (S)	37.5
Aluminum (Al)	2.07
Magnesium (Mg)	1.1
Silicon (Si)	0.634
Iron (Fe)	0.382
Titanium (Ti)	0.0624
Strontium (Sr)	0.0322

Tab.10: Mineral composition of gypsum

Mineral	Chemical composition	Amount [mass %]
Bassanite	$CaSO_4 \cdot 0,5H_2O$	82
Gypsum	$CaSO_4 \cdot 2H_2O$	7
Anhydrite	$CaSO_4$	8
Hydrotalcite	$Mg_6AL_2CO_3(OH)_{16} \cdot 4HO$	3

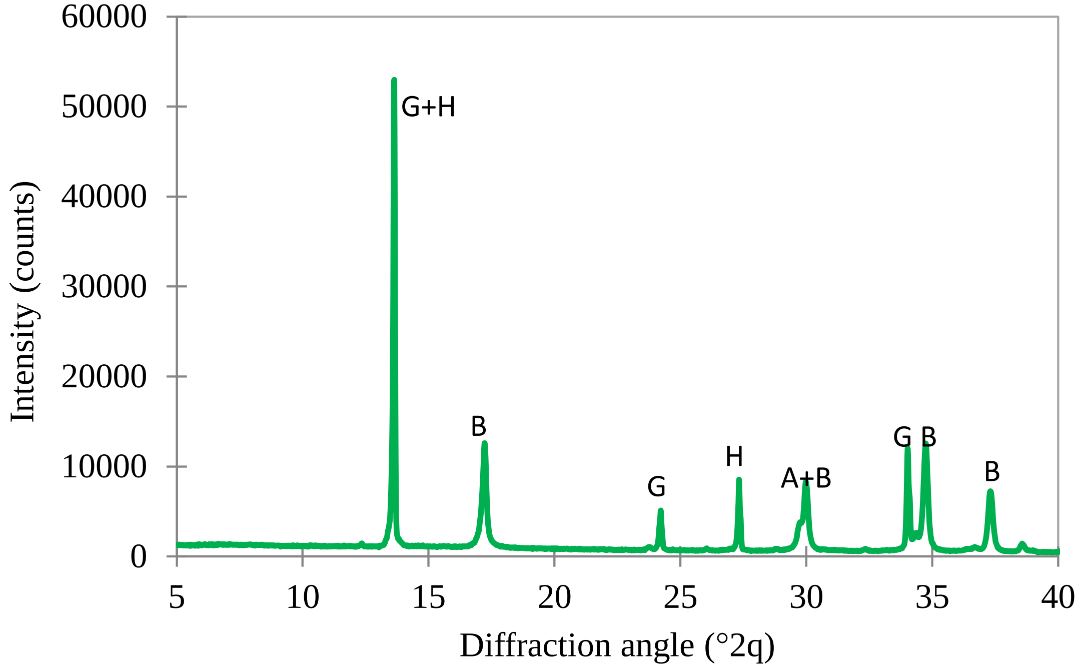
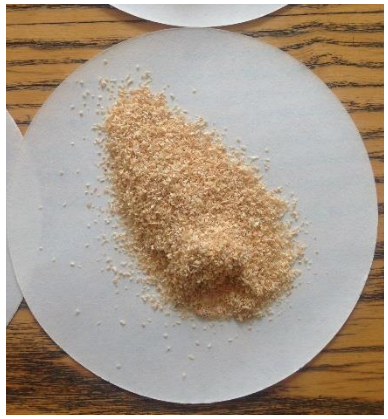


Fig.19: XRD pattern of gypsum (A-anhydrite, B- bassanite, G-gypsum, H – hydrotalcite)

As a filler the wood waste was used. The waste was obtained at the local sawmill after cutting, planning, and sanding of timber in the form of wood shavings. The wood originated from spruce (80%) and pine (20%). The typical shape of wood shavings can be seen in the Fig.20 The size of shavings was mainly between 0.25 to 8 mm. The granulometric curve is given in Fig. 21.

Size 0,25 - 0,5 mm



Size 0,5 - 1mm

Size 1-2mm

Size 2 - 4mm

Size 4 - 8mm

Size > 8 mm

Fig.20: Size of shavings

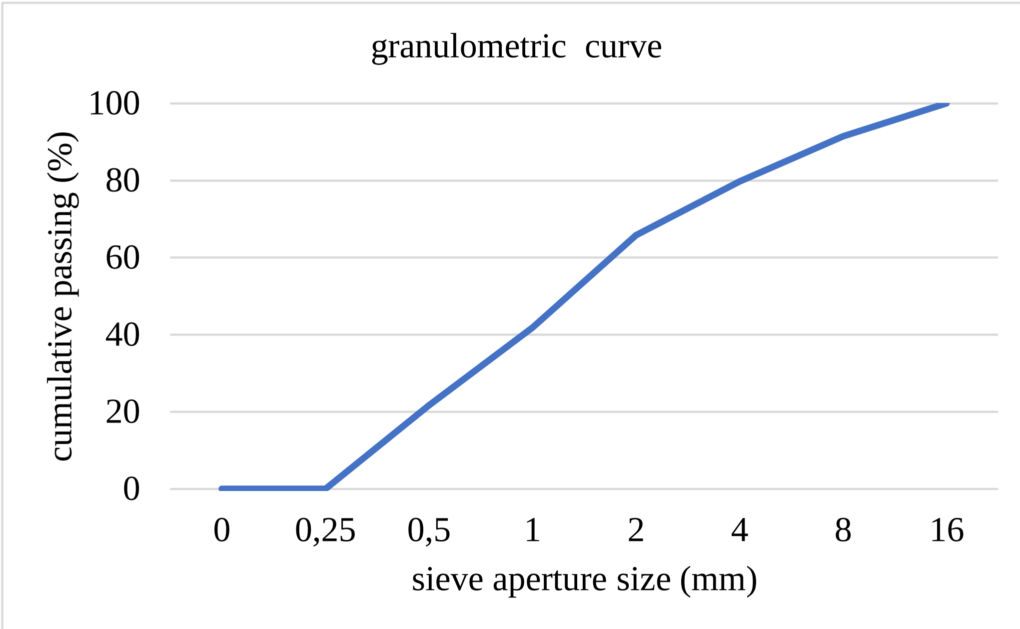


Fig. 21: Granulometric curve of wooden waste

4.4 Dimension of samples

Three distinct types of samples were molded for further testing. Water vapor specimens were cylinders with a diameter of 120 mm and a height of 30 mm, and cubes with edges of 70 mm were samples utilized for the mixes' fundamental physical characteristics and thermal conductivity. The final kind of specimen was a standard test prism 40 mm x 40 mm x 160 mm, which was utilized for mechanical parameters testing of the material.

4.5 Methods

4.5.1 Granulometry

When a sieve shaker paired with a stack of testing sieve, sample material is placed on the top sieve in the stack, and the sift shaker rotates while a hammer mechanism taps the top of the sieve stack, causing the contents to be separated. Flow through the test opening sieves, and operators may begin tracking the results. This technique is ideal for anyone who want to perform a simple particle analysis procedure.

Fig.22: sieve shaker machine picture [from https://www.indiamart.com/proddetail/sieve-shaker-machine-12947348948.html]

4.5.2 Mineral composition of raw materials (XRD):

X-ray diffraction analysis was used to determine the mineral content of raw materials. The PANalytical Aeris X-ray diffractometer was employed, which was outfitted with a CoKα tube that operated at 40 kV and 7.5 mA. Rietveld refinement was used to analyses the data, and quantitative mineral phases were generated using Profex software (ver. 3.12.1) [38]

How XRD works, this instrument consists of three main elements x-ray cathode tube, sample holder and X-ray detector. All diffraction methods begin with x-rays being emitted from a cathode tube or revolving target and then focussed on a material. You may examine the structure of the material by collecting diffracted x-rays. Diffraction will only occur if the way the x-rays and substance interact meets the conditions of Bragg's law [39]

This requires that:

- The angle of incidence is equal to the angle of scattering,
- The path length difference is equal to an integer number of wavelengths

This allows for a condition of maximum intensity, which then enables a calculation about the details of the crystal structure concerned.

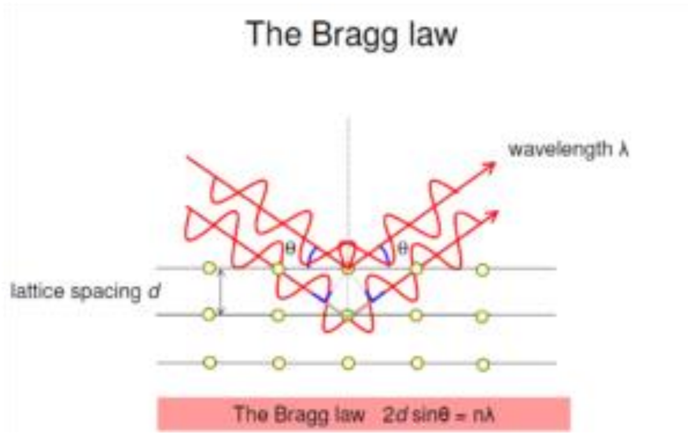


Fig .23: X-ray diffraction [39]

4.5.3 Scanning electron microscopy (SEM)

Equipment that generates a greatly enlarged picture by employing electrons instead of light to build an image. An electron cannon produces a beam of electrons at the top of the microscope. The electron beam travels through electromagnetic fields and lenses that focus the beam down toward the sample. The beam then passes through a pair of scanning coils or a pair of deflector plates in the electron column that deflect the beam in the x and y axes once the beam hits the sample electrons and x-rays are ejected from the sample detectors collect these x-rays back scattered electrons The SEM turns electrons into a signal that is sent to a screen, generating the final image [40].

4.5.4 Chemical composition (XRF)

An X-ray fluorescence (XRF) spectrometer is a non-destructive x-ray instrument used for routine chemical analyses of rocks, minerals, sediments, and fluids. When a sample is illuminated by an intense X-ray beam, known as the incident beam, some of the energy is scattered, but some is absorbed within the sample in a manner based on its chemistry.[41]

The sample is excited when this primary beam of X-rays illuminates it. The excited sample emits X-rays with wavelengths characteristic of the types of atoms present in the sample. This energy is released and then read by the detector, which indicates the time of the element based on the set of atoms

4.5.5 Compressive strength

The flexural and compressive strength of test samples (40x 40x 160 mm) were determined. The testing was performed out as a standard three-point bending test. The measurements were performed 20 days after the mixture was prepared. The compressive strength of the specimen halves left over from the flexural test was measured

4.5.6 Bulk density

For tested composites, bulk density ρ_v [kg/m^3] was calculated. The gravimetric approach was used to calculate the bulk density, in which the mass is detected by digital weight and the volume is calculated from a dimension measured by a digital calliper. The bulk density is calculated as a ratio between the mass and volume

4.5.7 Water vapour diffusion (dry cup method)

The cup method has two variants (dry cup method and wet cup method). The specimens (120 mm diameter, 30 mm height) were first insulated along their sides with two-part epoxy glue to guarantee one-dimensional water vapour diffusion, and then sealed in cups with silica gel on the bottom (dry cup method). Inside the cup, the silica gel formed an atmosphere with a relative humidity of roughly 5%, whereas the RH outside the cup was 50%. This was accomplished by storing the specimens in an air-conditioned room with a humidity of 50% and a temperature of 23 ^{0}C. (Fig. 24). [42]

Fig. 24. Dry cup with silica gel

The mass measurements of the cups containing the samples were subsequently performed daily for a 6-day period. The steady state value of mass gained derived by linear progression for the past five observations was used to calculate the water vapour diffusion permeability and coefficient.

The water vapour diffusion permeability δ [s] was estimated using the following equation:

$$\delta = \frac{\Delta_{m \cdot d}}{s \cdot \tau \cdot \Delta p_p}$$

where Δm [kg] is the amount of water vapour diffused through the specimen, d [m] is the thickness of the specimen, S [m^2] is the surface of the specimen, r [s] time corresponding to the transport of mass of water vapour Δm, and Δpp [Pa] is the difference in partial water vapour pressure in the air beneath and above the specific surface of the specimen.

Following that, the water vapour diffusion coefficient D [m^2•s^{-1}] was computed using the equation:

$$D = \frac{\delta \cdot R \cdot T}{M}$$

Where T [K] is the absolute temperature, M [$kgmol^{-1}$] is the molar mass of water, and R[$Jmol^{-1}.K^{-1}$] is the universal gas constant.

The water vapour diffusion resistance factor μ [-] was calculated using this formula:

$$\mu = \frac{Da}{D}$$

where Da [$m^2.s^{-1}$] is the diffusion coefficient of water vapour in the air

4.5.8 Thermal conductivity

Thermal conductivity λ [$Wm^{-1}. K^{-1}$] was measured by the device Isomet 2114 (Fig.25). It comes with two types of optional measuring probes: needle probes for soft materials and surface probes for hard materials. The measurement is based on an examination of the temperature response of the substance under consideration to heat flow impulses. Electrical heating is used to produce heat flow, using a resistor heater in direct thermal contact with the surface of the sample

The measurements in this paper were done using the surface probe. 3 sets of values of thermal conductivity λ [W/m^2K] and volume heat capacity c_ρ [were measured for each specimen and the mean value was calculated from them [42].

Fig. 25. Isomet 2114 in process of measurement

4.6 Composition and preparation of samples

Gypsum was combined with wood waste fillers for the preparation of the samples. The wood shavings were added in different amounts. Citric acid was used as a set retarder.

The mass ratio of dried gypsum powder to wood waste was 5% for the first sample (JB5) and it was increased 5% until the last sample. The gypsum dosage was always 500 g/batch. Setting retarder was added at a rate of 0.05% of the dry gypsum mass. In, a composites composition with lightweight fillers was devised.

Because of their varying porosity and surface the materials have different workability, so the amount of water in the composites with lightweight fillers had to be different and it was determined for 180 mm flow diameter by jolting table. Table 11 lists the composition of tested materials.

All samples were prepared by this way: To begin, the specified amount of dry gypsum and wood waste were mixed and stirred together in a bowl, then the specified amount of water and retardant were stirred together in another mixing bowl until the retardant dissolved. The water was then mixed with dry gypsum-wood mixture in the same bowl using an automated mixer. The mixing time was 4 minutes, which included 30 seconds of mixing at low speed (140 rpm), 30 seconds of mixing at high speed (285 rpm), 90 seconds of rest to remove the mortar from the bowl wall, and 60 seconds of mixing at high speed. The gypsum plaster was put into moulds and was not compacted. The samples' surfaces were levelled using a metal knife. The samples were unmoulded after one hour and then were stored in the room environment (temperature 22 ± 2°C, relative humidity 50 ± 5%). Samples were dried before tests at 40 °C for 24 hours.

Table 11: Composition of tested materials

Samples	Gypsum	Wood	Citric acid	Water
	[g]			[ml]
JB5	1000	50	0,1	500
JB10	1000	100	0,1	700
JB15	1000	150	0,1	900
JB20	1000	250	0,1	1100

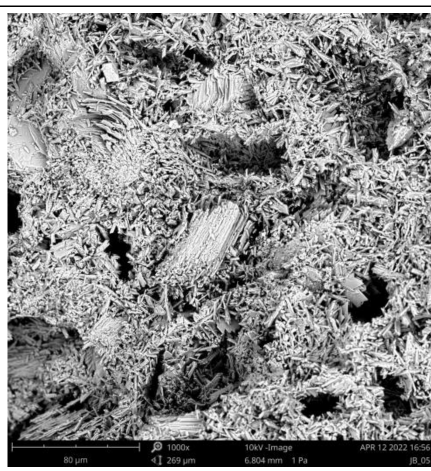
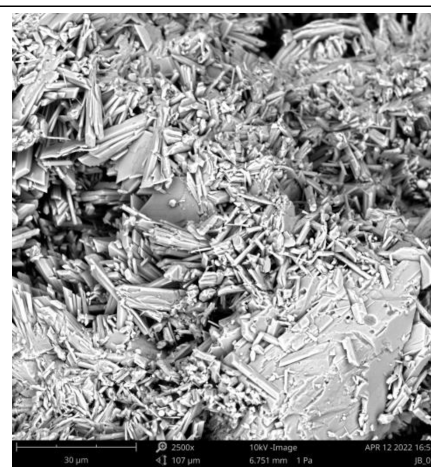
JB5 JB10 JB15 JB20

Fig.26: The structure of broken samples after strength test

5 Results and discussion

5.1 SEM

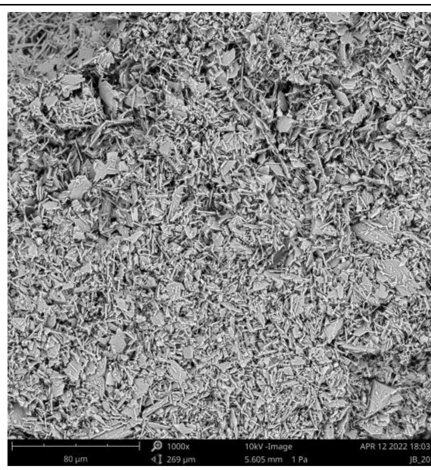
The structure of all samples was examined by the scanning electron microscope. We can clearly see by the pictures taken from SEM that structures of samples are different in terms of porosity. While there can be seen a lot of pores in the material JB5, in the materials with higher amount of wood (JB10, JB 15 and JB20) there can be seen that the number of pores decreases, because are gradually filled by the finest wooden particles. There can be seen that the contact between gypsum matrix and wood particles is good, there is no gap between them. The wood particles do not have the influence on the shape and size of gypsum crystals, which are nearly the same in each material.

	1000x	2500x
JB5		

JB10

JB15

JB20



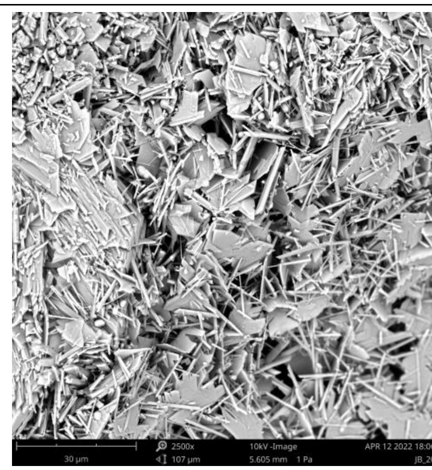


Fig.27. Microstructure of tested materials

5.2 Physical and mechanical properties

The bulk density and compressive strength are given in Tab.12

Tab.12: Basic properties of tested materials

Sample	Bulk density	Compressive strength
	kg/m^3	MPa
JB5	1218	6,04
JB10	951	2,8
JB15	824	1,9
JB20	701	1,05

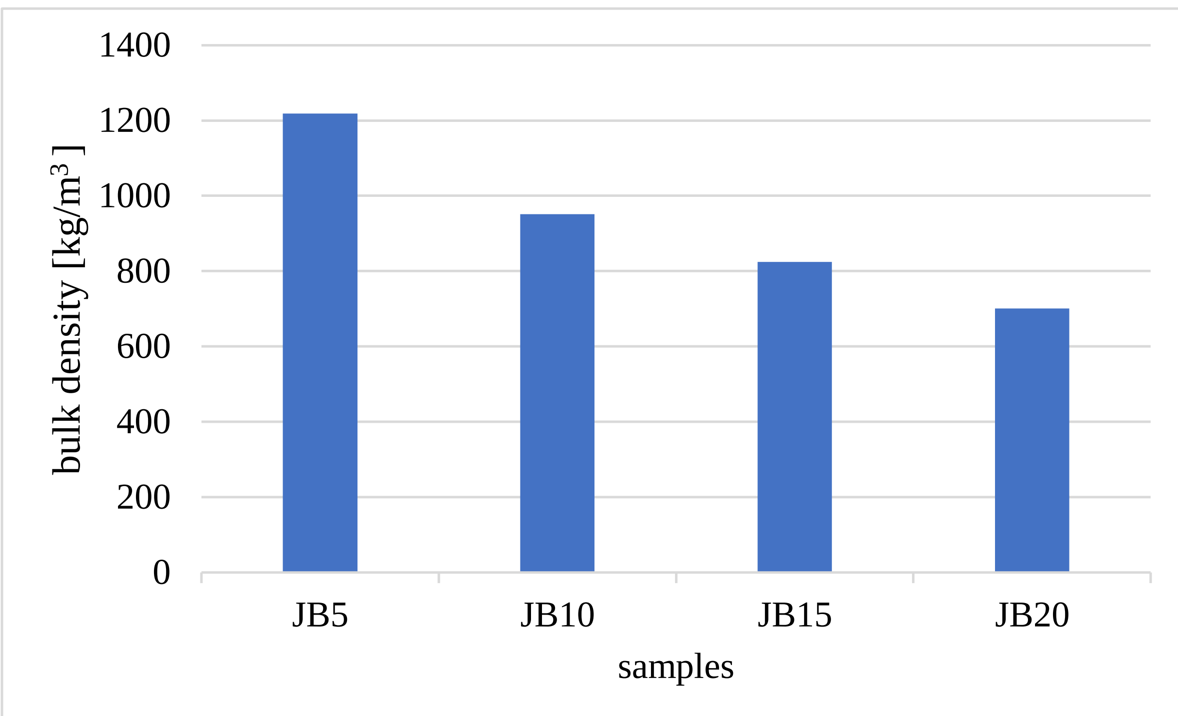


Fig.28. Bulk density

We can see the bulk density decreases linearly from JB5 to JB 20, because the wood is lighter than gypsum matrix and therefore with the increasing amount of wood the bulk density of materials decreases. This was expected phenomenon as discussed in chapter 3.3

As we can see in Tab. 12, the highest compressive strength was achieved by sample with lowest amount of wood waste and compressive strength decreased significantly with increasing amount of wood waste. There can be seen in Fig. 30 that the relationship between the bulk density and compressive strength is nearly linear. The compressive strength decreased even if the porosity of materials with higher amount of wood was lower, as can be seen in SEM images (Fig. 28). This is because the wood particles in the pores do not play role from the point of view of strength.

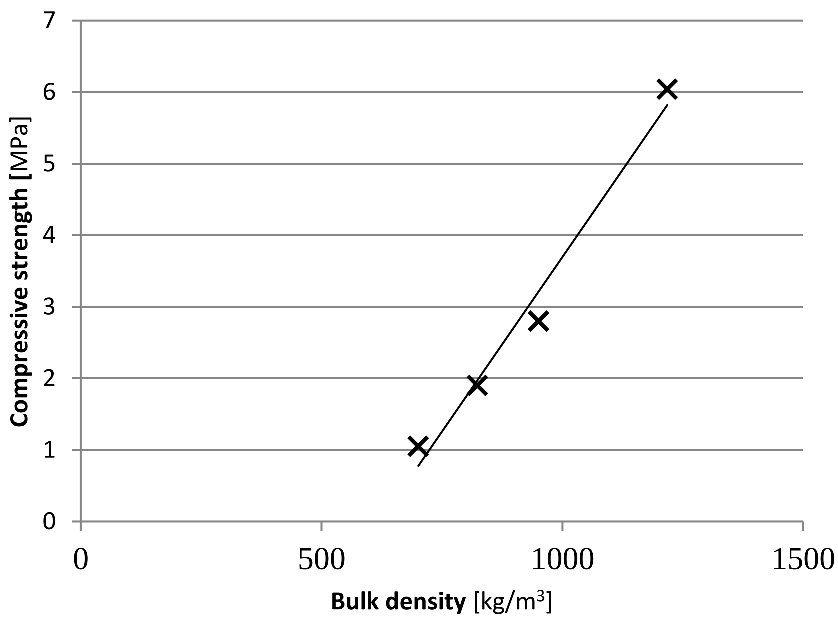


Fig. 29. The relationship between the bulk density and compressive strength

5.3 Thermal properties

Tab.13 shows the thermal properties of the studied materials in a dry state. The materials were measured 3 times for each sample and then average value of thermal conductivity λ and volume heat capacity c_ρ were calculated. From the sample JB5 to JB20 we can see than the values are decreasing. Gypsum is not considered to be thermal insulating material, nevertheless its thermal conductivity is lower than thermal conductivity of cement. When gypsum is mixed with wood (which can be considered as a thermal insulating material), the materials with better thermal insulation properties can be made. Material with 20% of wood can be used as a thermal insulation.

Tab.13: Thermal properties

Samples	Thermal conductivity λ	cp
	[W/mK]	[J/m^3.K]
JB5	0,4095	1,2605.10^6
JB10	0,2736	1,4826. 10^6
JB15	0,1994	1,4208.10^6
JB20	0,1775	1,434. 10^6

5.4 Moisture properties

The moisture properties are given in Tab. 14. There can be seen that with the increasing amount of wood from 5 to 15% the diffusion resistance decreases which is given by the fact, that wood is generally very open material. The water vapor resistance of material with 20% of wood is higher than that of materials with 15%, which can be given by the fact that all pores in this material are filled by fine wooden particles, as can be seen in SEM images (Fig. 28). Nevertheless, all tested materials can be considered as water vapor permeable.

Tab.14: Moisture properties

Sample	Water vapor diffusion permeability δ	Water vapor diffusion coefficient D	Water vapor diffusion resistance factor μ
	[s]	[m^2/s]	[-]
JB5	2,17.10^{-11}	2,5263.10^{-6}	9,393
JB10	2,413. 10^{-11}	3,3196. 10^{-6}	6,95
JB15	3,911. 10^{-11}	5,427. 10^{-6}	4,283
JB20	3,184. 10^{-11}	4,380. 10^{-6}	6,57

6. Conclusions

The primary goal was to find the best of gypsum - wood waste composite, which can be used as a cheap and sustainable material in a tropical climate of Angola. We can declare the experiment successful if we compare the obtained data to the data measured with the cited studies [22]. All the measured values are within the discussed behavior of the of previous experiments' results. All tested composites can be used as a building material, nevertheless material with 10% of wood waste will be my choice for the given purpose. Its strength is sufficient for less demanding construction, it is lightweight material and the thermal insulation properties are acceptable for this climate. Because of often rains in Angola the material must be protected from the water (e.g., by plaster) but its permeability properties enable fast drying, because it is rather open material.

Gypsum is a perfect material to be used if you are looking for a recyclable and affordable material, as the recycled gypsum has the same properties as the original gypsum. Nowadays with the big consideration in green building construction and low-cost materials, experts are looking for solution for the pollution problem, and one of this solution is looking for the best green materials environment friendly to use in the construction of future structures and then give a permanent retirement or hopefully the less use of the not so eco-friendly materials

By replacing traditional building materials with the created bio composites, the environmental effect will be reduced. To improve bio composite processing at the industrial level, more research should be done.

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