**The role of aluminum compounds and heat treatment in strengthening mineral fiber composite paper materials**

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**Abstract.** This paper looks at how aluminum-based binding compounds (Al2(SO4)3 and NaAlO2) and heat treatment (drying at 200 °C) affect the strength of composite paper-like materials made from mineral fibers (basalt and kaolin). The study carefully checks how fiber type, binder type and usage, and the environment's pH levels change the material's mechanical stability. The results showed the strength of samples made from basalt fibers goes up by 2.5 times with aluminum sulfate and high-temperature heat treatment. But these binders had a bad or neutral impact on kaolin fibers. The study also found that contact and convection drying methods work differently, and strength creation processes are unique in mineral fibers. Because they don't have many hydrophilic surfaces, “saturation consumption” has a different meaning in mineral fibers. The research shows that aluminum hydro complexes may create water-repellent structural links, which is helpful for making paper-like materials that stay strong even when wet. These findings are helpful for use in industry areas like filtering, technical packaging, and heat protection.

**INTRODUCTION**

There is a growing need for green, strong, and helpful composite materials. Paper-like materials made from cellulose and mineral fibers are used in different industries like technical packaging, filtering, building, and heat protection [1]. But we still need to make these materials more resistant to water and more mechanically steady. Research shows aluminum-based binding compounds (Al2(SO4)3 and NaAlO2) are key to making composite materials stronger. These compounds help fibers link better, especially when heat is used to treat them. The structure of mineral fibers like basalt and kaolin, how active the hydroxyl groups are on their surfaces, and how they react with binders decide what the final material properties will be [2]. This paper studies how different binding compounds (aluminum sulfate and sodium aluminate), drying methods (contact and convection), and pH levels change composite paper materials made from basalt and kaolin fibers. The goal is to find the best conditions that make mechanical strength better in both wet and dry conditions and to create a type of paper material that can be used in industry [3].

Composite materials made with kaolin fibers are stronger. Experiments with sodium aluminate show that composite paper made with basalt fibers is stronger. Aluminum sulfate works well with kaolin fiber, but not as well with other fibers [4].

When aluminum sulfate is replaced with sodium aluminate in basalt fiber samples, the material's strength increases by 2.5 times. The strength decreases in kaolin fiber samples [5]. How well a strengthening additive works depends on the fiber type, which will decide the best compound for composite strength.

Experiments show that aluminum hydroxide can strengthen mineral fiber-based materials. The next step is to find the best conditions to ensure aluminum hydroxide works well as a binder. The right amount of binder and key technological settings need to be set [6].

Past experiments looked at how paper made from annual plant cellulose with aluminum compounds gains moisture resistance when heated briefly at 150-200 °C. Moisture resistance appears because of hemiacetal bonds between fibers and changes in the bond's shape and energy in the aluminum complex [7].

When heated, the link between the fiber and aluminum ion changes from a zero shape to a dioxo shape through oxygen, raising the energy bond from 35-39 kJ/mol to 44-49 kJ/mol. As the strength of wet samples rises, so does their strength when dry. However, the specific role of these processes in making paper stronger when wet or dry has not been found [8,9]. So, studying how heat affects the strength of mineral fiber samples with an aluminum compound additive is important for both theory and practice. Based on this, the effect of three main factors was studied. The factor values are in a range, the binder use is from 5 to 30% of the mineral fiber mass, the pH environment in papermaking is a bit acidic (pH=4.5-5), neutral (pH=6.5-7) and a bit alkaline (pH=9-9.5), heat done at 200 °C [10].

According to thermogravimetric analysis, some molecules in the aluminum hydrocomplex’s inner coordination sphere are released with heat even at 180 °C. Because of this, some samples are dried at 120 °C in an oven and then heated at 200 °C for 15 minutes [11].

**MATERIALS AND METHODS**

This study looked at how different mineral fibers (basalt and kaolin) and binders (aluminum sulfate and sodium aluminate) affect how strong, heat-resistant, and moisture-resistant composite paper-like materials are. It also examined how heat treatment and drying methods (contact, convective, vacuum) affect the final product qualities [12,13]. The study focused on basalt fiber (from the Asmosoy deposit, refined), kaolin fiber (a mineral-based particulate material), binders like aluminum sulfate (Al2(SO4)3) and sodium aluminate (NaAlO2), and auxiliary components like cellulose from annual plants (Jerusalem artichoke, cotton, cotton stalks) [14].

**RESULTS AND DISCUSSION**

Figure 1 shows how the components experimented with affect the strength of paper-like materials containing basalt fiber as a reinforcing agent. Heat treatment helps the material's strength only when aluminum sulfate is the binder. For the other components, a slightly acidic environment is ideal for forming the material. In general, greater strength correlates with more binder. However, there are some unpredictable values within particular binders. For Al2(SO4)3, the material attains peak strength in a slightly acidic environment when the binder content is 10–15%; yet, increasing the content to 30% lowers it. In contrast, in a slightly alkaline environment, strength rises continuously across all binder content levels.

(a)

(b)

(c)

**Fig. 1.** Strength of basalt fiber material; a) pH 4.5-5, b) pH 6.5-7, c) pH 9-9.5

The trend is less obvious for the NaAlO2 binder component. The mineral fiber's characteristic changes these correlations. Specifically, when using kaolin fiber (Figure 1), the material's strength is not related to Al2(SO4)3 produced in a slightly acidic environment. Heat treatment does not improve strength in any scenario. The binder's characteristic has a varied impact on the material's strength when basalt fiber is employed. For instance, with the basalt fiber component, greatest strength happens at 30% content and in a slightly alkaline environment, whereas with kaolin fiber, it is minimal and noticeably lower. The strength of cellulose-made paper is linked to the creation of stronger hemiacetal bonds and changes in the form and energy of several hydroxyls with the aluminum ion. Hemiacetal bonds cannot form in mineral fiber samples, and the amount of surface hydroxyls is much lower than in cellulose fibers, which causes the observed constant strength of paper-like materials.

(a)

(b)

(c)

**Fig. 2.** Heat treatment was found to be not useful for mineral fiber samples, so this factor was later removed from the study. The research was broadened to examine how the material's environment affects its strength, noting that this influence is not consistent; a) pH 4,5-5, b) pH 6,5-7, c) pH 9-9,5

The impact of pH levels on the drying method of kaolin fiber materials and its resultant strength was studied. The intensity of the drying process is where the effect is seen. Five drying methods were tested: convection in a 105 °C drying oven, under an infrared lamp, air drying, and two contact methods using electricity and a «Rapid-Ketten» sheet former-dryer under vacuum at 45-50°C.

(a)

(b)

(c)

(d)

**Fig. 3.** Shows how the drying method and pH environment influence the strength of kaolin fiber material;   
a) pH in ~4.5, b) pH in ~6.3, c) pH in ~7.5, d) pH in ~9.2

Changing the drying method alone can noticeably change a material’s strength under similar conditions (sodium aluminate samples, casting at pH = 9.2). In some instances, samples air-dried or vacuum-dried were so weak that their strength could not be properly measured. Strength differences linked to the drying method were bigger in samples with aluminate sodium additives than in those with aluminum sulfate. This seems linked to the higher hydration of hydroxides from sodium aluminate. Literature suggests this. The top strength was reached with contact drying for around half the samples, while convective drying worked best for the others.

The results from testing wet sample strength are somewhat unique. To test wet samples, they were soaked in a container of water at 18–20 °C for two hours, then squeezed between three sheets of filter paper, and tested right after squeezing.

Current standards say paper is water-resistant if it keeps at least 15% of its original dry strength when fully soaked. Most fiber-based paper fails to be water-resistant unless specially treated, losing almost all its strength when wet.

Materials, for example, a paper made of kaolin fiber and two types of binder, keep their full strength even when wet. The biggest drop in wet strength does not exceed 15%, so this paper is called water-resistant. A full review of the results is needed, comparing them with cellulose materials that are different in type, and with other bond formation mechanisms.

When looking at things that affect how strong a composite material is, the saturation point is not seen even when the aluminum compound use is 30%. In plant fiber-based paper making, the saturation point is when enough aluminum compounds are used that all possible cellulose fiber hydroxyl groups can have a coordinated bond with aluminum hydrocomplexes.

If more aluminum compounds are added than what is needed to reach the saturation point, they act as an inert filler instead of a binder. This makes the material weaker.

Experiments with cellulose fiber-based materials support this idea. But test results suggest that the connection mechanism described above does not fully explain mineral fiber-based materials.

Since mineral fibers have fewer surface hydroxyls than cellulose fibers, the saturation point should happen with less use of aluminum compounds in mineral fibers. But tests have not confirmed this. This means that the way aluminum compounds form bonds in mineral fibers is different from how they do so in cellulose materials.

Research on how aluminum compounds strengthen plant fiber paper says that when the temperature rises during dehydration of aluminum’s semi-nuclear complexes, some hydroxyl bonds turn into stronger, water-resistant bonds, which makes the paper very water-resistant. Our research found that mineral fiber-based paper-like materials are water-resistant. To explain this, we can look at how plant fiber paper is made.

Strength develops faster with contact drying. This is especially true for samples with less surface area that could potentially form bonds. In plant fiber materials, this includes things like sanitary paper or recycled fluting. At the same time, bag paper made from finely ground kraft cellulose shows high strength when convection dried in a flekt-type device. This drying effect may be caused by surface tension. Fibers able to create a strong material are pulled together by capillary contraction, creating bonds. Sheet materials made from these fibers are very shrinkable. Fibers that can’t form bonds between themselves without binders create a cavity structure. This structure will not shrink and the menisci go into the cavities as the inside water starts to evaporate.

If strong materials can be made using convective drying, where strength depends on the bonding between particles, this drying method may not be good enough when the strength is controlled through binders. In this case, a contact drying method may be needed. This approach gives both heat and mechanical pressure, resulting in better contact between the particles (similar to hot pressing).

Some samples were dried in air, and some in a vacuum, at low temperatures (40-45 °C). The water resistance of the samples was high. Under these conditions, it is possible that the method of aluminum compounds for cellulosic materials, along with extra heat treatment, improved water resistance. The reason for improved water resistance is that many dispersed structures can fall apart as the dispersion medium dries. As liquid evaporates from the pores, tiny curved surfaces form between liquid and air.

Here is a rewrite of the text you sent:

Surface tension of liquid is shown as an open capillary with radius g pull the liquid column, as if a pressure of 2 (t/g) is applied from the outside to the side surface of the capillary.

If the elasticity of the walls is enough, the capillaries compress as the liquid evaporates. Then the radius of curvature leads to an increase in pressure in the capillary, which causes the radius to decrease again. Approaching capillary walls allow contacts with hydrogen bonds during the next liquid removal stage. The stated idea applies simply to paper made from well-ground cellulose fibers.

In the case of mineral fibers, this idea also applies to wet parts that are developed at the water-air boundary and are related to the moisture after the samples being studied are moistened and then the water is squeezed out between layers of filter paper. Bonds created with the help of binders included during the wetting of samples are partly or fully broken and replaced by bonds that appear due to external gravitational forces. The starting wet strength mechanism of paper from plant fibers is similar. The main difference is that the level of initial wet strength in paper is lower than the strength of dry paper. The indexes of similar wet strength materials made of mineral fibers are higher than those of materials like paper made from them. Sometimes the wet strength of mineral fiber materials is higher than that of similar dry materials, which does not go against the suggested mechanism.

Thus, figuring out and looking at the kind of drying on the strength of mineral fiber materials involves a number of factors of kaolin fiber materials in this case. It is hard to make directions because their roles are opposite. Yet, it needs to be noted that it is important to take how the drying method affects the strength of the material into account when making technological rules for the production of paper-like composites from mineral fibers on certain paper and cardboard making machines, because the drying methods are different on different machines: contact, convection, and radiation.

To end the research works on forming paper-like composite materials, note one more factor related to the geometry of mineral fibers. In particular, mineral fibers are longer than other fibers and tend to break into pieces, which lowers the uniformity of the macrostructure.

**CONCLUSION**

Some useful study findings were made based on the researches. Composite materials made from basalt fibers show 2.5 times higher strength when treated with aluminum sulfate, especially after heat treatment (200 °C). This is explained by the formation of strong structural bonds that have fully reacted with the binder.

For kaolin fibers, the results were good with other binder compounds instead of aluminum sulfate. This shows that it depends on the level of chemical fit between the binder and fiber surface. The drying method (contact or convection) greatly affects the final mechanical properties of the composite material. Contact drying (for example, pressing) is better, especially for materials with weak fiber bonds, which greatly increases strength. The idea of saturation consumption is important for cellulose materials, but this was not fully seen in mineral fibers. This is because mineral fibers have low hydroxyl activity. Researches prove that it is possible to make paper-like materials that keep their strength even when wet, where the nature of the binder compounds, the level of heat treatment, the drying method, and pH are the main factors to manage. These ideas serve as a study base for making practical directions and introducing them into industrial production for making high-quality, wet-resisting composite materials based on mineral fibers.

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