formed. A 5-year research program was undertaken to examine the recyclability of numerous PSA formulations. The essential characteristics of PSAs that made them removable under typical recycling conditions were identified. New guidelines for new PSA formulations were developed for adhesive manufacturers. Acceptable PSAs remain intact, thus were removed primarily by pressure screening, under typical warm, alkaline conditions used in recycling. Adhesives that were successfully removed during processing in pilot plant trials by pressure screening, cleaning, and flotation were subsequently confirmed in recycling mill trials. This research resulted in recyclable PSAs for the USPS products. The guidelines are likely to be adopted by other manufacturers of paper likely to be recycled.

See also: **Papermaking**: World Paper Industry Overview. **Pulping**: Bleaching of Pulp; Chemical Pulping; Environmental Control; Mechanical Pulping.

Further Reading

Akhtar M, Blanchette RA, Myers G, and Kirk TK (1998) An overview of biomechanical pulping research. In: Young and Akhtar MRA (eds) *Environmentally Friendly Technolgies for the Pulp and Paper Industry*. New York: John Wiley.

Dence CW and Reeve DW (eds) (1996) *Pulp Bleaching: Principles and Practice*. Atlanta, GA: TAPPI Press.

Gullichsen J and Fogelholm CJ (eds) (1999) *Chemical Pulping*. Helsinki, Finland: Fapet Oy.

Kenealy WR and Jefferies TJ (2003) Enzyme processes for pulp and paper: a review of recent developments. In: Goodwell N and Schultz (eds) *ACS Symposium Series 845. Wood Deterioration and Preservation: Advances in Our Changing World*.

Klugness JH, Stroika ML, Sykes MS, *et al.* (1999) *Engineering Analysis of Lightweight, High-Opacity Newsprint Production by Fiber Loading*, 1999 TAPPI Papermaking Conference, March 1–4, Atlanta, GA.

Weinstock IA, Barbuzzi EMG, Wemple MW, *et al.* (2001) Equilibrating metal-oxide cluster ensembles for oxidation reactions using oxygen in water. *Nature* 414(6860): 191–195.

Physical Properties

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Structural Introduction

Paper has existed for over 2000 years and during that time it has found a myriad of uses, each of which requires its own unique set of paper properties. For example, high-quality printing papers need to be smooth, bright, opaque, dimensionally stable, and have good ink absorption characteristics. Paper towels, on the other hand, need to be soft, water-absorbent, and have a certain amount of strength when saturated with water. Neither of the two needs to have the strength characteristics required of packaging papers. In this article we will describe the most common paper properties referred to by papermakers and converters in their daily operations. For convenience, these properties will be grouped into the following four categories:

1. Structural properties.
2. Mechanical properties.
3. Appearance properties.
4. Barrier and resistance properties.

Lastly, we will consider the effects of atmospheric relative humidity on paper properties. Details about paper property testing will not be presented here unless they are necessary to define a specific property. You are referred to the Further Reading section for information about testing instruments and procedures.

The Structural Characteristics of Paper

Structural characteristics describe how the fibers are arranged in a sheet of paper. The topics of interest are listed in **Table 1**.

Basis Weight and Grammage

Papermakers keep track of their production in terms of tons produced and sell their products either on a weight basis or an area basis. This practice gives rise to the definition of the basis weight of paper as the weight, in pounds, of a predetermined number of sheets of a specified size. The number of sheets is known as the ream size. The size of the sheet is known as the basic size. The most common ream size is 500 sheets. There are a variety of basic sizes, several of which are listed in **Table 2**.

The system for specifying basis weight is very cumbersome. A simpler approach is taken in the SI system of units where the weight of paper is

Table 1 Structural properties of paper

Basis weight and grammage
Thickness
Formation
Directionality
Two-sidedness
Porosity
Smoothness or roughness

Table 2 Examples of basic sizes

Paper grade	*Dimensions (in.)*
Book, bible, offset, blotting	25×38
Bond, ledger, mimeo, writing	17×22
Glassine, news, tissues, wrapping	24×36
Postcard, wedding, Bristol	22.5×28.5
Cover stock	20×26

Table 3 Typical basis weights and grammages of various papers

Paper grade	*Basis weight (lb)*	*Grammage ($g\,m^{-2}$)*
Grocery bag, sack	30–60	49–98
Bond	13, 16, 20, 24	48, 60, 75, 90
Folder stock	100–225	163–366
Corrugating medium	26	127
Kraft linerboard	16, 33, 38, 42, 47, 69	127, 161, 186, 205, 229, 337
Tissue and toweling	10–35	16–57
Newsprint	30	49

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expressed in terms of grams per square meter, or grammage. **Table 3** gives some typical values for the basis weight and grammage of different kinds of paper.

Thickness (Caliper) of Paper

The thickness, or caliper, of paper is defined as the perpendicular distance between the two principal surfaces of paper and paperboard under specified conditions. The thickness of paper and paperboard ranges from 0.0003 in. for capacitor paper to 1 in. or greater for some construction boards.

Thickness is a very important property for the end-use and converting requirements of most grades of paper and paperboard. For example, the overall thickness of a book is directly related to the thickness of the paper used. The thickness of index cards and file folders determines how many can be filed in a given space. Thickness uniformity is also very important for most papers.

Formation, Directionality, Two-Sidedness

Paper is made from a mixture of heterogeneous particles having different shapes, densities, and chemical compositions. This mixture is subjected to a sheet-forming process where the flows are accelerated and drainage and filtration occur in one direction. The sheet is pulled in one direction during drying and substances are added to the outer surfaces of the formed sheet. In addition, the two-dimensional nature of a paper web imposes severe constraints on the different ways that sheet components can arrange themselves. The specific paper properties related to material distribution are called formation, directionality, and two-sidedness.

Formation The overall uniformity with which fibers and other solids particles are distributed in paper determines the formation of paper. Formation is an important property for printing papers—poor formation produces poor print quality. In the extreme, poor formation can also influence the strength of paper and its ability to absorb fluids uniformly.

Directionality Many paper properties are directional in nature. In other words, a given paper property might have one value when measured along one direction of the sheet and another value when measured at right angles to the first direction. The source of this behavior lies primarily in the relative alignment of fibers in the paper web. Few, if any, fibers have their axes aligned in directions other than parallel to the plane of the sheet. In addition, within the plane of the sheet, a majority of the fibers will often have their axes oriented toward the direction of forward movement on the paper machine. This preferential orientation arises as a result of accelerating forces exerted on the fibers in the headbox and on the forming section of the paper machine. Tension exerted on the sheet during drying also serves to enhance the effect. The terms 'machine direction' or 'grain direction' are assigned to the direction of paper parallel to the direction of paper machine travel, while the direction at right angles to the machine direction is called the cross-direction, cross-grain, or against-the-grain direction. The major influence of directionality lies in its effect on many mechanical properties of paper.

Folding, creasing, and scoring can be done more readily along the grain direction. The higher machine direction stiffness is taken advantage of in the design of file folders and some types of packages. Because the directionality of paper is so important in converting operations, the grain direction of sheets will always be indicated on the container of paper shipped from the mill to the converter. With roll stock, there is no ambiguity as to which direction is the machine direction.

Two-sidedness In addition to influencing the fiber orientation in paper, the manufacturing process can lead to nonuniform distribution of components through the thickness, or z-direction, of the sheet. Near the bottom side of the sheet, which is in contact with the fourdrinier wire during web formation and which is referred to as the wire side, there is a relatively low concentration of filler and fines. As you move through the sheet toward the top side, which is called the felt side, the filler and fines content increases. The outer surfaces represent the two extremes in component distributions and have very different characters.

The differences between the wire and felt sides of paper are significant due to their influence on other properties. As a rule, the gloss and smoothness of the two sides will be different. The two sides act differently in printing and it is important to identify them when setting up printing presses.

Porosity of Paper

Ordinary papers are about 50% air, by volume. Some of the air is present inside fibers, but most of it resides in pores within the sheet structure whose diameters are on the order of 1 μm (1×10^{-6} m). The ratio of pore volume to total volume is called the porosity of the sheet. This property, while being fundamentally very important, is rarely measured in papers except occasionally in laboratory studies. However, a related property, air permeability, is often determined. Air permeability is defined as the property of a paper that allows air to flow through it under a pressure difference across the sheet. It is a structure-related property depending on the number size, shape, and distribution of pores in the sheet. It should be emphasized that air permeability is not a measure of porosity and the two terms should not be used interchangeably.

Smoothness or Roughness of Paper

It is common to say that paper has a 'smooth' or 'rough' texture, meaning that the surface irregularities are small or large. A wide range of surface textures are available in papers today, ranging from very smooth, highly calendered papers to rough, uncoated grades of paper produced from coarse softwood fibers.

The quality of a paper surface is often referred to as its finish, which may be spoken of as high or low, good or poor, smooth or rough. Finish combines all those characteristics encompassed by the senses of sight and touch and, although a useful term, is an indefinite one from a technical standpoint. Appearance and mechanical qualities may also contribute to the perceived smoothness of paper.

Smoothness is a very important property in a wide variety of paper. Some papers are intentionally given very rough surfaces, while others must be very smooth, and still others must be carefully controlled somewhere in between. Smoothness is important in printing papers and in paper that serves as coating rawstock. It is possible for a paper to be too smooth and exhibit a tendency to slip in converting processes.

The Mechanical Properties of Paper

A sheet of paper, by virtue of its structure, exhibits the same general mechanical attributes as other structures encountered by the engineer in the field of construction materials. The term 'strength properties' is often used to refer to these characteristics of paper. They determine the durability and resistance to applied forces exhibited by paper during manufacturing operations, converting processes, and end-use performance.

While the fundamental mechanical properties of paper have been studied extensively, the more useful mechanical properties are applied in nature and are used for quality control during the manufacture and converting of paper and for specification of the specific qualities associated with each paper grade. **Table 4** lists the most common examples of such mechanical properties.

The mechanical properties commonly adopted by the paper industry are designed to yield values representing the resistance of a sheet of paper to stresses of various kinds at the point of paper rupture. The tests are arbitrary, as shown by the different specimen sizes, conditions, and instruments specified by the various test methods.

Tensile Properties

In a tensile strength measurement, a paper specimen of defined width and length is clamped between two jaws. The test instrument then causes the separation distance between the two jars to increase, which exerts a tensile stress (pulling stress) on the specimen. A mechanism is provided which indicates the tensile force when the specimen ruptures. This force is referred to as the tensile breaking strength (**Figure 1**). Most instruments can also indicate the stretch and tensile energy absorption of the specimen simultaneously with the tensile breaking strength.

Table 4 Common mechanical properties

Tensile properties
- Tensile breaking strength
- Stretch
- Tensile energy absorption

Bursting strength
Tearing resistance
Folding endurance
Bending stiffness

Figure 1 Illustration of a test specimen clamped in a tensile tester. During a test the specimen is stretched as the upper clamping jaw moves away from the fixed lower clamp. The tensile force being applied at the instant of rupture is called the tensile breaking strength. (TAPPI test method T 494 om-88.)

Tensile Breaking Strength

Tensile strength is a direct indication of the durability and potential end-use performance of a number of papers that receive direct tensile stresses in use, such as wrapping, bag, gummed tape, cable strapping, twisting papers, and printing papers. A certain minimum tensile strength is required of any paper that undergoes a web converting operation where it is subjected to tensile stresses while being pulled through the process. Printing papers are primary examples.

Stretch

The stretch of paper at rupture is usually expressed as a percentage of the original length of the test specimen. Stretch properties are important because they affect the way a paper withstands sudden impacts.

Tensile Energy Absorption

A tensile specimen absorbs energy during a tensile test. This phenomenon is known as tensile energy absorption (TEA) and it is directly related to a paper's ability to withstand sudden strains without breaking. TEA is strongly influenced by stretch and the most common way to increase the TEA in paper is to increase its stretch.

Tensile breaking strength, stretch, and TEA are known as directional tests because their values depend upon the direction (machine-direction versus cross-direction) in which a test specimen is cut.

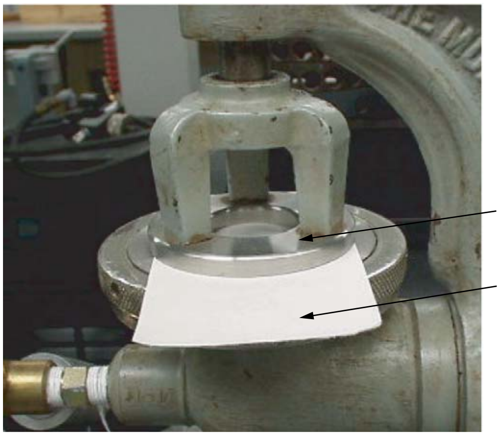

Figure 2 Bursting strength test. During the test a rubber diaphragm expands against the clamped test specimen causing the specimen to bulge into the annulus in the upper clamp. The test value is taken to be the pressure being exerted against the rubber diaphragm at the point of specimen rupture. (TAPPI test method T 403 om-91.)

Bursting Strength

Bursting strength is defined as the pressure required to rupture a paper specimen when it is held between annular clamps and subjected to pressure from one side. This causes the specimen to deform into an approximately hemispherical shape until failure occurs by rupture (**Figure 2**). The bursting strength test is one of the oldest tests used by the paper industry. The best use of the burst test is as a convenient, general indicator of strength or toughness of paper.

Tearing Resistance

The most common tearing resistance property used in the paper industry is called Elmendorf tearing resistance, after the specific instrument employed by the industry. The Elmendorf test measures the mechanical work required to continue a tear – which has already been started – through a fixed length of specimen using an Elmendorf tear tester. The mode of the tear is out-of-the-plane of the paper. **Figure 3** illustrates the tester.

The Elmendorf tear is particularly valued as a test for paper and paperboard, which will be subjected to tearing strains during converting or in end-use. Bags, wrapping papers, tissue papers, book, magazine and newsprint paper, and paperboard for bottle and can carriers are all papers or products where Elmendorf tear values are deemed important.

Elmendorf tearing resistance is affected by the direction in which the test is run, with the cross-direction tearing resistance being higher than the machine-direction tearing resistance in most instances.

Figure 3 Internal tearing resistance tester. A paper test specimen is clamped in a segmented clamp; the right side is fixed to the instrument base and the left side is attached to a segmented pendulum. The test specimen is slit along a line between the two clamp segments prior to the test. Thus, the test measures the force required to continue an internal tear within the paper specimen. During a test, the pendulum is released and swings upward (left to right in the figure), carrying the left clamp segment with it. This motion tears the paper specimen in a direction perpendicular to the plane of the paper in its original clamped configuration. The resistance exerted by the tearing specimen against the swinging pendulum is taken to be the internal tearing resistance. (TAPPI test method T 414 om-88.)

Folding Endurance

Many papers, such as currency and map papers, undergo repeated folding during end-use. The requirement here is one of durability or resistance to wear over a long period. In these instances, the folding endurance test is applicable.

As a rule, the machine-direction folding endurance is higher than the cross-direction folding endurance. Different papers exhibit a wide range of folding endurance values ranging from essentially zero double folds for very weak papers such as facial tissues to several thousand double folds for currency paper. **Figure 4** contains a picture of a paper specimen clamped in a folding endurance tester.

Bending Stiffness

Stiffness is defined as the resistance to a force causing a member to bend. Stiffness is very important to the end-use performance of many papers. For example, file folders and index cards must support themselves upright during use. Playing cards, posters, cups, and plates are also examples of paper that must have good stiffness in use. Stiffness is one of the most important mechanical properties of paperboard used in packaging. Packages must resist deformation, or bulging, when being filled and when the contents settle in a package while it is sitting on a shelf in the store. Folding cartons and corrugated shipping containers must also withstand bending stresses from loads imposed on them from containers stacked above.

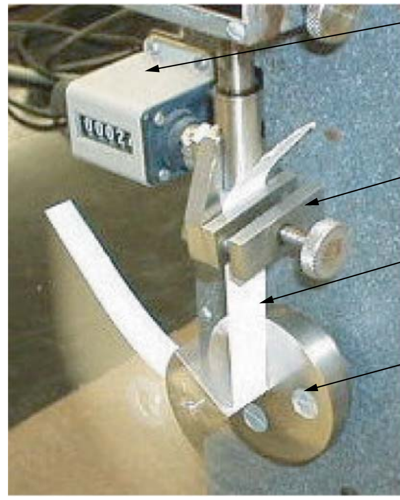

Figure 4 Folding endurance. In the folding endurance test the paper specimen is clamped between a rotating lower clamp and a stationary, spring-loaded upper clamp. The specimen is then subjected to a continuous folding motion of $\pm 135^\circ$ away from the unfolded configuration at the lower clamp while under tension from the upper clamp. The test value is taken to be the number of complete folds the specimen will undergo without rupture. (TAPPI test method T 511 om-96.)

Table 5 Factors affecting paper stiffness

Major	Thickness
	Young's modulus of pulp
	Restraint during drying
	Moisture content
	Surface treatments (wax, starch)
Minor	Fiber–fiber bonding
	Fiber orientation

A number of factors affect stiffness, several of which are listed in **Table 5**.

Stiffness can be thought of as a function of the product of Young's modulus and the thickness raised to the third power. Thus, thickness is a most important factor in controlling stiffness. As much as a threefold increase in machine direction stiffness can be achieved by increasing the tension on the sheet during drying. Cross-direction stiffness will be decreased by this action, however. Conversely, increasing the moisture content of paper will significantly decrease its stiffness. **Figure 5** illustrates a commonly employed stiffness-testing instrument.

Since stiffness is greatly affected by thickness, it is not surprising that paperboards exhibit by far the highest stiffness values, while tissue and toweling papers are the least stiff. In fact, a prerequisite for soft papers is that they have very low stiffness.

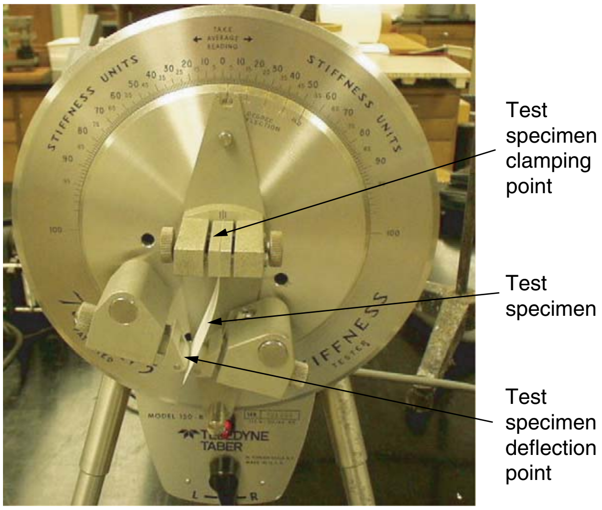

Figure 5 Taber stiffness test. The Taber stiffness test determines the bending moment necessary to deflect the free end of a vertically clamped specimen 15° from its center line when a load is applied 50 mm away from the clamp. This test is most commonly applied to paperboard. (TAPPI test method T489 om-92.)

The Appearance Properties of Paper

In this section, we will consider the appearance properties of paper, called transparency, opacity, brightness, color, and gloss.

A small piece of paper contains several million fibers and millions of small pieces of fibers that were torn away from the pulp fibers during the refining process. When illuminated with a beam of light, the fibers, fines, and filler particles in a sheet of paper cause some of the light rays to be reflected in all directions from the surface of the sheet. Since there are a great number of reflecting particles within the sheet, a great amount of light reflection occurs inside the sheet also. As a result of these multiple reflections, the transmitted light rays that emerge from the other side of the sheet and the reflected rays that emerge back out of the surface of the sheet are not parallel, but travel in all directions. This is indicated schematically in **Figure 6**.

The name given to this type of behavior is diffuse scattering. Hence, most of the light incident on white bond paper is either diffusely reflected or diffusely transmitted since the individual fibers and filler particles are essentially colorless. Materials that diffusely transmit light are said to be translucent. For white papers, the properties opacity, brightness, transparency, and gloss are all functions of the diffuse reflectance and diffuse transmittance of visible light. Colored papers involve light absorption, the topic to be discussed next.

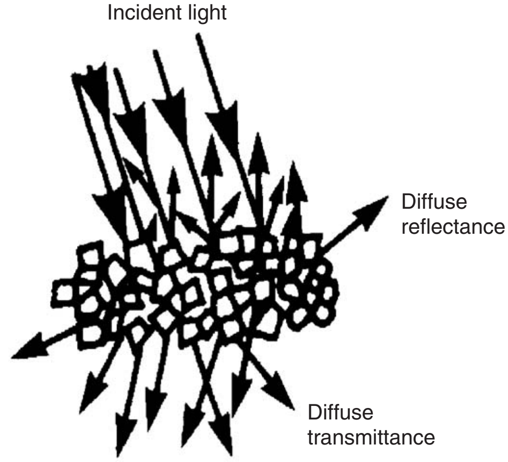

Figure 6 Schematic representation of diffuse reflectance and diffuse transmittance. Reproduced, with permission, from Scott WE and Abbott JC (1995) *Properties of Paper: An Introduction*, 2nd edn. Atlanta, GA: TAPPI Press.

The Color Properties of Paper

Color is used for identification, to attract attention, and to emphasize distinguishing characteristics in commodity papers and packaging. All white papers contain small amounts of dyes called 'tinting dyes.' These colorants produce a slight colored shade, or tinge, that is distinctive of a particular product.

The color of a sheet of paper is determined by the light absorption characteristics of its components. Dyes and colored pigments accomplish nearly all of the light absorption in colored papers. If you plot the diffuse reflectance from a thick pad of colored paper at different wavelengths across the visible spectrum, the resulting curve is called a spectral reflectance curve. Spectral reflectance curves for bleached, uncolored pulp, and the same pulp separately dyed with red, blue, and yellow dyes appear in **Figure 7**.

As is shown in the figure, the principal effect of the dyes is to cause the characteristic spectral reflectance curve of the white pulp to shift, and thus to cause its intrinsic color to change. By selecting industrial dyes having the desired light absorption characteristics, it is possible to create or match a full range of colors for any substrate within the physical limitations of the system involved.

Papermaker's Brightness

Another very important appearance property is called papermaker's brightness. True brightness refers to the lightness or overall spectral reflectance of paper, the energy distribution of the illuminant, viewing conditions and the characteristics of the viewer. Papermaker's brightness, on the other hand, is based on a measurement of the reflectance by white

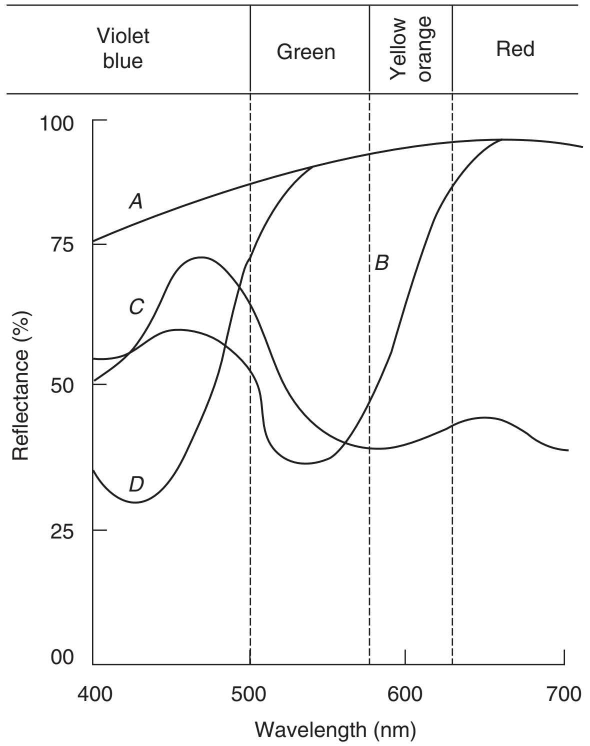

Figure 7 Typical spectral reflectance curves for dyes and undyed pulp. *A*, Bleached, uncolored pulp; *B*, *A* plus red dye; *C*, *A* plus blue dye; *D*, *A* plus yellow dye. Reproduced, with permission, from Scott WE and Abbott JC (1995) *Properties of Paper: An Introduction*, 2nd edn. Atlanta, GA: TAPPI Press.

or near-white papers at a single wavelength, 457 nm. Papermaker's brightness is primarily a measure of freedom from pulp yellowness associated with the presence of lignin and other impurities left by incomplete bleaching.

Unbleached kraft pulp will typically have a papermaker's brightness of 25–30%, while fully bleached kraft pulp will fall in the 80–90% range, depending upon its intended use. Newsprint papers have brightness typically in the 65–75% range.

Gloss

Gloss is the characteristic of a paper surface that causes it to reflect light at a given angle of reflection in excess of the diffuse reflection at that angle. Gloss is the degree to which the surface simulates a perfect mirror in its capacity to reflect incident light. In the case of a mirror, almost all of the light falling on the surface is reflected at an angle equal to the angle of incidence. This is known as specular reflection. Conversely, a completely matte surface will reflect the incident beam in all directions and the surface will appear the same from every angle.

Gloss measurements on paper have been made at many different angles of incidence, but most measurements on paper are made at an angle of 75° from the normal. Highly glossy papers, such as waxed papers, are measured at 20° from the normal. **Table 6** indicates the gloss values measured for a variety of papers.

Table 6 The gloss of different papers compared to polished black gloss as 100

Type of paper	*Gloss*
Lacquer-coated papers	96
Magazine cover	70
Machine-coated book	51
Supercalendered book	30
English finish book	12
Typewriter bond	6
Household waxed paper	57[a]
Bread wrapper	63[a]

[a] Measurements made at 20° from the normal. All the rest were made at 75° from the normal.

Reproduced, with permission, from Scott WE and Abbott JC (1995) *Properties of Paper: An Introduction*, 2nd edn. Atlanta, GA: TAPPI Press.

Opacity and Transparency

Transparency ratio is the preferred method of evaluating highly transparent materials, while opacity measurements are more suitable for relatively opaque papers.

Transparency

Transparency is important in tracing, reproduction, and packaging papers, to name a few. A completely transparent paper would be one that transmitted, without scattering, all of the light falling on it, and a clear view of an object would be had when the paper was placed between the object and a viewer, regardless of the distance between the paper and any object being viewed through it.

The transparency ratio of a paper, which is a true measure of transparency, is the ratio between the parallel transmittance of light and the total transmittance of light. Glassine, the most transparent paper, exhibits 10–40% parallel transmittance for a total transmittance of 60–85%. On a comparable basis, say 65% total reflectance, a tissue paper would have only 3% parallel transmittance.

Opacity

A perfectly opaque paper is one that is absolutely impervious to the passage of all visible light. The black paper used to wrap photographic films can properly be called 'opaque,' and most paperboards are opaque for all practical purposes. Many papers cannot be classified as opaque, yet opacity is a very important property for them. Printing, bond, and writing papers are good examples where this is true.

Opacity is determined by the amount of light transmitted by a paper. If all of the incident light is transmitted and none is reflected or absorbed, then the opacity will be zero. If no light is transmitted and all of it is reflected or absorbed, the opacity will be 100%. Most papers fall between these two extremes.

The Barrier and Resistance Properties of Paper

Introduction

Papers often come into contact with liquid water while being converted into final products or during their end-use. If it is desired that absolutely no water pass through the web, then the paper is said to exhibit barrier properties. Many packaging products must meet this requirement. Since paper webs are porous, some other material must be combined with it to produce the desired barrier characteristics. Plastic and wax coatings and metal foils are examples of materials that are employed for this purpose.

On the other hand, if it is necessary that a paper only retard or slow down the rate of penetration of liquid water in order to function properly, then the paper is said to exhibit resistance properties. Writing papers, offset printing papers, and coating base stock papers are examples of papers that must resist the penetration of liquid water in order to function effectively. However, if these papers come into contact with water over a long time period, then they will allow its penetration. Hence, they do not have barrier properties.

Another important group of papers must be able to absorb large amounts of water rapidly in use. These are called waterleaf papers. Examples are paper towels, facial tissues, filter paper, and blotting papers.

Table 7 lists the most important factors that affect water penetration rate in paper.

Table 7 Factors that influence the rate of penetration of fluids into paper

Porous structure of the web
Degree of wetting of fibers by penetrating liquid
Wetting time
Fiber swelling
Diffusion

Paper webs are porous, having micron-size pore diameters. Those pores that connect the upper and lower sheet faces provide pathways for liquid penetration. The degree of wetting of fibers by liquids is expressed by the angle between the liquid and solid surface when the two come into contact. **Figure 8** illustrates this phenomenon.

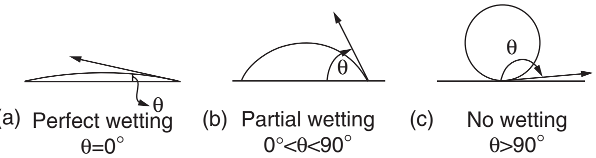

Figure 8 The different contact angles associated with perfect wetting, partial wetting, and no wetting. Reproduced, with permission, from Scott WE and Abbott JC (1995) *Properties of Paper: An Introduction*, 2nd edn. Atlanta, GA: TAPPI Press.

A certain time is required for a liquid to wet paper. This time is called the wetting time. Wetting times ranging from 0.005 s to 0.3 s have been measured for different papers and liquid water.

Paper specimens increase in size (swell) when brought into contact with liquid water. The ratio of such swelling in the different sheet directions has been reported to be 1:2:50 for the machine-direction, cross-direction, and thickness-direction, respectably. This behavior will alter the internal pore structure of paper and affect the interactions that occur between the sheet and water.

It has been hypothesized that the diffusion and subsequent condensation of water molecules contained in the water vapor accompanying the advancing liquid water front aid in the penetration of liquid water through paper. It is expected that this will be a second-order effect that is only important in very dense papers.

The Influence of Environmental Conditions on Paper Properties

Light, temperature, moisture vapor, and other atmospheric components can all affect paper properties. Of these factors, moisture vapor is by far the most important. Since moisture content can have a significant effect on paper properties, paper testing is usually done under well-defined atmospheric conditions – for example, 23°C and 50% relative humidity in the USA.

The effect of moisture content on mechanical properties is quite complex, as illustrated in **Figure 9**. The figure illustrates that nearly all possible behavior is observed. However, practically all mechanical properties will be adversely affected by relative humidities above 60%.

Changes in moisture content also affect the dimensional characteristics of paper. **Table 8** lists the major effects observed.

Paper expands in all directions when its moisture content increases, with the greatest expansion

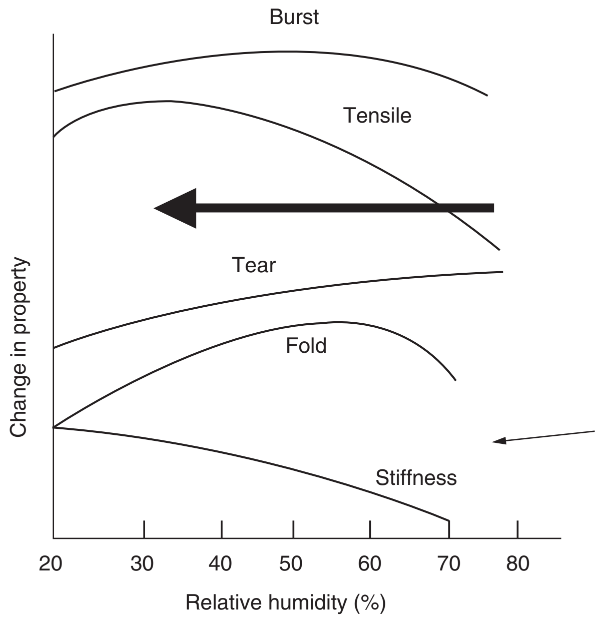

Figure 9 Effects of relative humidity on the mechanical properties of paper. Reproduced, with permission, from Scott WE and Abbott JC (1995) *Properties of Paper: An Introduction*, 2nd edn. Atlanta, GA: TAPPI Press.

Table 8 Influence of moisture content on the dimensional stability of paper

Expansion and contraction
Cockle
Curl
Wavy edges
Tight edges

occurring perpendicular to the plane of the sheet. Cockle refers to the 'puckering' that often accompanies an increase in moisture content. Curl refers to the tendency to 'roll up' into a tube exhibited by many papers as their moisture content increases. Wavy edges and tight edges are ramifications of curl that occur in stacks of paper where moisture content changes occur mostly at the exposed edges of sheets.

The dimensional changes listed in **Table 8** may be reversible or irreversible. In the latter case, they are almost always undesirable and it is necessary to guard against changes in sheet moisture content during conversion or end-use.

Conclusion

This concludes our overview of the most common paper properties important in the manufacture and use of paper. It was pointed out that paper has a highly complex structure and cannot be rigorously treated in fundamental terms. Consequently, papermakers and end-users rely on more empirical and arbitrary ways to characterize the common paper properties employed in manufacturing control and end-use performance. These properties can be grouped into the four categories of structural, mechanical, appearance, and resistance properties that provided a framework for this discussion. Many paper properties are also affected by atmospheric humidity and temperature conditions and the papermaker must take this into account when controlling the final moisture content of manufactured paper. End-users also often control the temperature and relative humidity of their operations because of this.

The intention of this discussion was to provide an introductory overview of the most common physical properties of paper. More detailed treatments can be found in the Further Reading section. In addition, there are other more specialized properties, such as electrical conductivity, that could not be discussed here. You are also referred to the Further Reading section for treatments of these subjects.

See also: **Packaging, Recycling and Printing**: Packaging Grades. **Papermaking**: Overview; Paper Grades; Paperboard Grades; Tissue Grades; World Paper Industry Overview.

Further Reading

Biermann CJ (1996) Paper and its properties. In: *Handbook of Pulping and Papermaking*, 2nd edn, pp. 158–189. London: Academic Press.

Conners TE and Banerjee S (eds) (1995) *Surface Analysis of Paper*, pp. 1–350. London: CRC Press.

Hahn LD (1992) *Testing Guidebook*, pp. 1–40. Atlanta, GA: TAPPI Press.

Kocurek M and Kouris M (eds) (1992) *Pulp and Paper Manufacture: Mill Control and Control Systems – Quality and Testing, Environmental, Corrosion, Electrical*, vol. 9, 3rd edn, pp. 1–233. Atlanta, GA: Joint Textbook Committee of the Paper Industry.

Levlin J-E and Soderhjelm L (eds) (1999) *Papermaking Science and Technology. Pulp and Paper Testing*, vol. 17, Helsinki, Finland: Fapet Oy.

Mark RE, Habeger CC, Borch J, and Lyne MB (eds) (2002) *Handbook of Physical Testing of Paper*, vols. 1 and 2. New York: Marcel Dekker.

Niskanen K (ed.) (1999) *Papermaking Science and Technology*, vol. 16, *Paper Physics*, pp. 1–324. Helsinki, Finland: Fapet Oy.

Scott WE and Abbott JC (1995) *Properties of Paper: An Introduction*, 2nd edn. Atlanta, GA: TAPPI Press.

Smook GA (1990) *Handbook of Pulp and Paper Terminology*, pp. 1–447. Vancouver, Canada: Angus Wilde.

Smook GA (2002) Properties and testing of pulp and paper. In: *Handbook for Pulp and Paper Technologists*, 3rd edn, pp. 332–344. Vancouver, Canada: Angus Wilde.

TAPPI Test Methods (2002–2003). Atlanta, GA: TAPPI Press.