MBAA TQ vol. 53, no. 2 • 2016 • pp. 82–88

Commonly Used Finings and Their Application for Settling and Stability

Andrew Fratianni
Gusmer Enterprises, Inc., Mountainside, NJ, U.S.A.

ABSTRACT

Consumers have long placed a great importance on brilliantly clear beer as a sign of quality. In recent years, craft brewers have produced hazy beers that have gone on to achieve a high level of acceptance in the market. However, any beer with any amount of haze may no longer be acceptable for many craft beer consumers. A review of the most common finings and their application in the brewery will help the brewer to produce a consistent product no matter the level of haze specified.

Keywords: Haze, Finings, Stability, Process aids

For more than a century now, consumers have indicated both a preference for and a willingness to pay for brilliantly clear beer.

At the same time, the craft brewing segment, a more recent development, not limited to North America only, continues to see significant growth.

To keep up with the overall demand for their beer, these craft breweries are expanding and growing their markets. Production volumes increase, transport distances become greater, and process times need to be optimized, but in the end, brewers still have limited control over their product once it leaves the loading dock. One of the major problems that arises is the formation of haze. If left unchecked, this haze can lead to bits, particles, and sediment in the package (2).

With this growth, the focus on product quality and product consistency has become increasingly important as consumer awareness increases, transport and storage conditions are not always ideal, and the competition from other breweries intensifies.

Despite both the introduction of many new styles of beer and significant change in the marketplace, beer haze still remains a primary focus of brewers. Haze of any type, and at any level, might have once been acceptable for craft brewers, but these brewers now realize that if there is to be haze in the beer, it needs to be a specific amount of haze in the beer over the entire shelf life of the beer.

For craft brewers, producing hazy beer meant a less aggressive filtration or even complete elimination of it, sometimes relying only on centrifugation of beer. But with enough years of experience to deal with the many possible variations of natural raw materials, the reliance on a centrifuge alone may sometimes not be sufficient. These brewers have noticed that sometimes their beers are becoming too hazy, frequently near the end of the expected shelf life. The change is noticeable, and it is enough to generate both comments and concern.

Against these increasing demands, the goal is to produce beers with limited haze or no haze, while optimizing process times and decreasing the intensity of any filtration required or eliminating it completely. To meet this goal, brewers have traditionally turned to finings or process aids. Some finings are very quick acting, resulting in a rapid sedimentation, while others remove the precursors to haze, which given enough time will form haze itself and eventually sediment.

This paper describes both adjuncts and process aids. They may also be referred to as finings and auxiliary finings. To avoid confusion, this paper often uses the term "process aids."

Deciding upon the types and amount of finings or process aids requires weighing a host of factors including process times, costs, and equipment, as well as each brewer's preferences.

So before throwing away all the old textbooks and old equipment that only the largest breweries use, this paper will review haze formation, some of the more common fining materials that can be used to help clear the beer, how they are produced, and how they function.

Haze Formation

Before looking at ways to limit or prevent the formation of haze, a brief description of what haze is and how it is formed is in order. Only by first understanding the problem can a brewer then decide how to best to deal with it.

Haze, or lack of it, is often termed "stability." Today, this haze is most often a nonbiological haze, meaning that the causes are not from yeast, bacteria, or other organisms present

Andrew Fratianni began brewing beer at home at the tender age of 14. His newfound popularity in school led him to become a brewer. After graduating from New York University he headed to Portland, Oregon, where he started working in the craft brewing industry, and he went on to pass the Institute of Brewing AME exams while at the University of California, Davis. He has worked for Stroh and has been brewmaster for Pabst Brewing in China and DG Yuengling and Son. Andrew has worked as a product manager at brewery equipment manufacturer A. Steinecker Maschinenfabrik, has been a BASF Corp. senior technical sales representative for PVPP applications in the beer, wine, and the beverage industry, and since January 2014 has been the East Coast technical sales representative for Gusmer Enterprises, Inc., where he looks after beer, wine, juice, and spirits accounts. He is a member of the Master Brewers Association of the Americas, the Association of Brewing Chemists, and the Institute of Brewing and Distilling.

E-mail: afratianni@gusmerenterprises.com

http://dx.doi.org/10.1094/TQ-53-2-0424-01

in the beer, whether intentionally or not. The most commonly encountered sources for nonbiological haze are protein and polyphenol, and there are many texts that deal with this (1–11,13–21) (Fig. 1). These come primarily from the malt and hops used in brewing. Sometimes the haze can also come from starch and metals. The process aids described here primarily help to reduce the amount of protein and polyphenol in the beer, thus limiting haze formation in package. Some are also used to settle yeast in the beer. They are also called fining agents.

Use of process aids without regard to any other good brewing practices will render their use almost completely worthless. Aside from these process aids, limited oxygen pick-up and cold storage temperatures should be first and foremost on every brewer's mind after safety and efficiency.

Haze in beer is categorized into two different types (20):

1. **Chill haze** is haze formed at 0°C that dissolves when beer is warmed to 20°C. Particle size is 0.1–1.0 µm, and it is formed via hydrogen bonds. It is a reversible reaction.
2. **Permanent haze** is haze formed at 0°C and remaining when beer is warmed to 20°C. Particle size is normally 1.0–10.0 µm, and it is formed via covalent bonds. It is not a reversible reaction.

For the brewer, there are three possible options in combatting haze formation. Yes, it is a battle!

1. Reduce the amount of precursors that can cause haze.
   - Use of kettle finings, cellar finings.
2. Accelerate the formation of haze—then remove it prior to packaging.
   - Use of cellar finings.
3. Reduce the intensity of haze and consume beer before haze intensity becomes unacceptable.
   - Use of kettle finings, cellar finings.

All these methods will be rendered more effective with good brewing practices.

One important aspect of haze formation to keep in mind: as Delcour et al. noted, "prefilter haze contains mainly carbohydrates and protein while polyphenol participation in haze formation increases after final filtration" (4).

If the haze is formed after final filtration, this means that it will form in the bottle, keg, or can, out in the market, where a brewer no longer has control over the product. Further, this also means that a brewer must choose carefully the means to control haze while the beer is still in the brewery.

How Finings Work: Stokes' Law

Brewers have often turned to the use of finings to help speed up the clarification of young beer by quicker settling of the particles in the beer. Even today, with the latest developments of process technology, this method is still employed. Depending upon the type of process aid used and the brewing process, particle formation and settling can occur over anywhere from minutes up to days and weeks. The use and desired effect are left to the individual brewer.

Early brewers may not have known it, but the settling is governed by Stokes' law, which determines the settling velocity of particles. In this case, it is solids in a liquid. By looking at the individual factors in this equation, brewers will be able to benefit from a clear understanding of how Stokes' law works and how to use it to their advantage.

The settling velocity is determined by the relationship between the following factors:

- the gravitational pull of the earth or centrifuge, if employed
- the difference in density of the particle and the density of the beer
- the particle size of the sediment

By looking at the equation (Fig. 2), it becomes clear that the brewer has most control over the diameter of the particle, *d*. Fortunately for brewers, this yields a significant result.

Before the development of filters and widespread use of process aids, long storage of beer at low temperatures yielded similar results. It still works today, but the number of tanks and the amount of space required make it an expensive option (Fig. 3).

One way to see Stokes' law in action and to understand it better is to look inside an old can of paint. Oil-based paints seem to illustrate this phenomenon more readily, even though nowadays there might be only a few such examples remaining. After a long and quiet storage, the pigment has begun to settle, leaving behind the clear, amber-colored solvent on top. This same settling phenomenon is also happening in beer, and fortunately for us brewers, at a much faster pace.

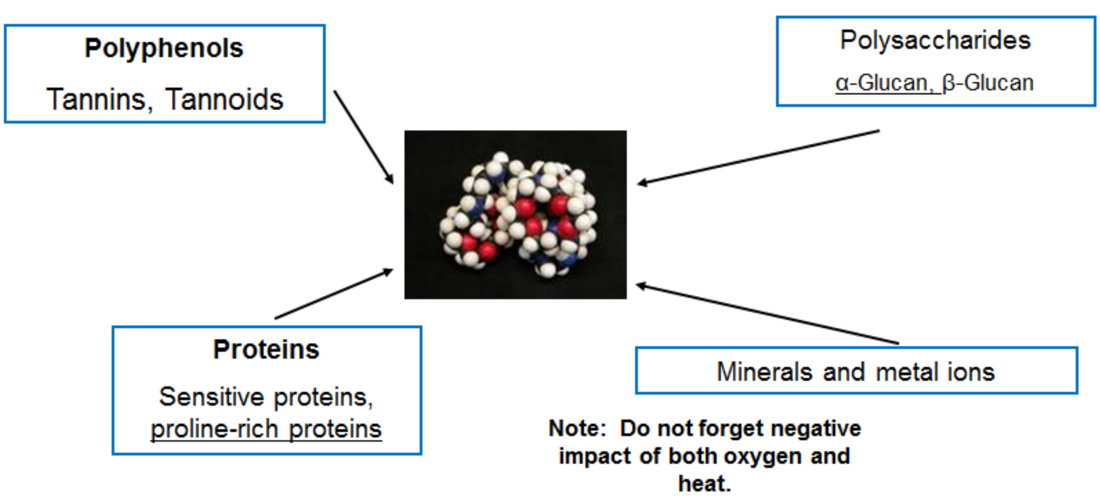

Figure 1. Potential components of nonbiological haze. Colloidal haze formation through polymerization and aggregation. Image courtesy of BASF SE.

Alternatively, head to the brewhouse and watch a sample of hot wort cool in a large flask. As it cools, the hot break will form and start to settle. In either case, Stokes' law is at work.

Depending upon the addition point in the brewing process, fining additions help to produce a clear wort prior to fermentation, settle beer prior to filtration, or limit haze formation in package.

This can be accomplished in the following ways:

- in the wort and fermentation via hot break, cold break, and yeast flocculation
- prior to filtration and packaging, affecting yeast, sediment, and haze in package

Precursors from the brewing process have an effect on beer colloidal stability. They can lead to the formation of nonbiological haze. The haze is most often formed from protein-polyphenol interaction. It is not harmful but is frequently considered a defect, especially in light-colored beers and filtered beers. This haze formation coincides with the development of a less desirable, "harsher" bitterness (2)—in addition to other flavor changes.

The following sections review the basic production and use of the most commonly used finings.

Commonly Used Finings

This paper will cover two brewhouse finings added during boil (carrageenan and polyvinylpolypyrrolidone [PVPP]) and five finings added after the end of fermentation (silica gel, silica sol, PVPP, tannin, and isinglass).

$$V_m = \frac{g\,(\rho_s - \rho_m)\,d^2}{18\mu}$$

V_m = settling velocity
d = particle diameter
ρ_s = particle density
ρ_m = liquid density
g = acceleration due to gravity
μ = viscosity of the beer

Figure 2. Stokes' law. Settling velocity is the speed at which the particles will fall. Particle density is a fixed number that we cannot change. Before the use of centrifuges, acceleration due to gravity (*g*) was always fixed and could not be changed on planet Earth.

Figure 3. Storage cellars in a modern brewery.

Carrageenan

Carrageenan is a gelatinous polysaccharide extracted from red seaweed. It is used as a kettle fining to help settle protein in the hot break in the whirlpool as well as in the cold break in the fermenter, and it aids in flocculation of yeast after fermentation (Fig. 4).

Background. Literature shows that the seaweed was recommended as cure for respiratory ailments in Ireland in the early 1800s. The plant was found in abundance in Carrigan Head, County Donegal, on the Northwest coast of Ireland. It is also called "Irish moss" (6).

Knowledge of the plant and its processing came with Irish immigrants to the United States and Canada, especially after the potato famine of the 1840s. The industry developed rapidly in North America after the start of World War II and the concurrent disruption of supply from Japan and the Pacific. The 1950s saw further development for the food industry. The first MBAA paper describing carrageenan appeared in 1964.

Today, the main commercial sources for carrageenan are *Chondrus crispus* from the North Atlantic and *Eucheuma cottonii* from the South Pacific.

There are three main commercially available classes of carrageenan, and each one has different molecular structure:

- Kappa has one sulfate per disaccharide and forms strong, brittle gels.
- Iota has two sulfates per disaccharide and forms elastic gels.
- Lambda has three sulfates per disaccharide and has no brewing value.

E. cottonni provides more kappa-carrageenan than *C. crispus* on a per weight basis. Brewers may find that less needs to be dosed for a desired effect (22).

Production

- **Raw material.** Red seaweed is washed and cooked at high pH to increase gel strength.
- **Semi-refined.** The cooked seaweed is rinsed, dried, and milled.

Figure 4. Granular and tablet forms of carrageenan. Image courtesy of Gusmer Enterprises, Inc.

- **Refined.** The semi-refined carrageenan is concentrated by alcohol extraction, washed, dried, milled, and blended. This additional step removes cell walls and other plant matter. Typically, it is more efficient than semi-refined carrageenan but also more expensive.

Brewing-Specific Considerations

- Kappa-carrageenan is a brittle gel former, forming compact trub in the whirlpool.
- Iota-carrageenan is an elastic gel former, and a small addition helps to form a more cohesive trub.
- Lambda-carrageenan is not considered useful for brewers. It is used for thickening of foods and has no application in the brewing industry.

Application

- Carrageenan is added to the kettle approximately 10–20 min before the end of the boil for:
  - proper dissolution and activation of kappa carrageenan
  - sterilization of carrageenan
- Dose rate: 1–6 g/hL (10–60 ppm). Suppliers have optimization guidelines for you.

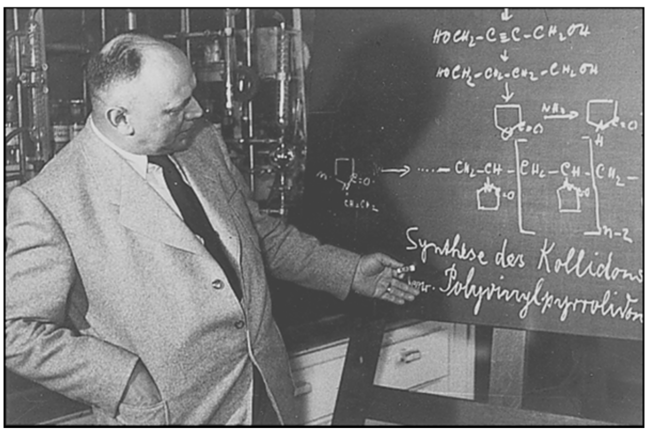

Figure 5. Walter Reppe explaining synthesis of polyvinylpyrrolidone, a prior development to polyvinylpolypyrrolidone. Image courtesy of BASF SE.

Preparation

- Tablet form requires no preparation. Simply count or weigh and add to kettle 10–15 min before the end of boil.
- Powder or granular form may need hydration prior to kettle addition. Check with your supplier. Add 20 min before the end of boil. Some forms are organic.

PVPP

PVPP is a white, insoluble powder that readily adsorbs polyphenols in beer.

Background. PVPP was invented by BASF, and the material can trace its origins to research begun in the 1930s. In beer, it readily adsorbs polyphenols that could bond to proline in the beer and form haze. It is available in a single-use and a regenerable form. The difference is only in the particle size. The single-use form offers convenience and ease of use. Regenerable PVPP requires a separate filter downstream of the primary beer filter and must be regenerated with caustic soda after filtration.

Development of PVPP for Brewing

1939	BASF Chemist Walter Reppe (Fig. 5) develops synthesis of polyvinylpyrrolidone (PVP).
1954	William D. McFarlane discovers PVP as a beer stabilizer.
1957	Approval for soluble PVP as a beer stabilizer in Canada, Sweden, and Denmark.
1964	Scandinavian breweries replace soluble PVP with crosslinked PVPP.
1973	Approval for use of PVPP as a beer stabilizer in Germany.
1980	Development of regenerable PVPP for beer stabilization.

Production

PVPP is a synthetic product. The final steps in production involve the polymerization and crosslinking of PVP to form PVPP, an inert substance (Fig. 6).

Through hydrogen bonding, PVPP is able to adsorb polyphenols (Fig. 7). PVPP is almost exactly identical to proline, which makes for a strong reaction of the PVPP with polyphenols in beer. Proline is one of the few amino acids not utilized by brewer's yeast and is a major haze former in beer.

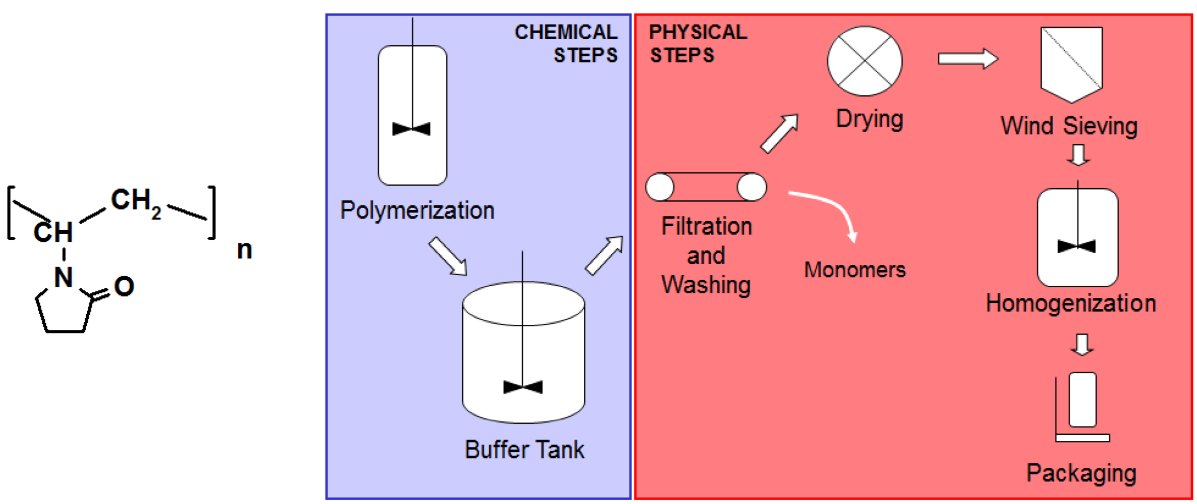

Figure 6. Polyvinylpolypyrrolidone (PVPP), left, and the production process for PVPP. Image courtesy of BASF SE.

Application

After fermentation, add to cold beer in-line during beer transfer or add in tank and allow to settle. It can also be added to the kettle at the same time as carrageenan.

- Dose rate: Beer up to 65% malt
  - PVPP alone: 10–30 g/hL (2.5–7.75 lb/100 U.S. bbl)
  - PVPP with silica: 10–20 g/hL (2.5–5.0 lb/100 U.S. bbl)
- Dose rate: Beer more than 65% malt
  - PVPP alone: 25–40 g/hL (5–10 lb/100 U.S. bbl)
  - PVPP with silica: 10–30 g/hL (2.5–7.75 lb/100 U.S. bbl)
- Contact time: Not less than 5 min

Preparation

- Single-use PVPP is mixed for 1–2 h in cold de-aerated water to allow for proper hydration and swelling. Apply CO_2 sparge if available.
- Regenerable PVPP is cleaned with caustic soda and prepared for subsequent use.

Silica Gels: Hydrogel, Xerogel, and Silica Sol

Silica gel is an amorphous, inert material that, owing to its unique properties, selectively adsorbs haze-active proteins while excluding foam-positive proteins.

Background. Silica gel is haze specific, and its use will not remove foam-positive proteins from the beer (5,7,8,17). It produces low sludge volumes and low losses.

Properties of Haze-Active and Foam-Positive Proteins

- Haze-forming proteins—10,000–60,000 Da, isoelectric point 3.0–5.5, hydrophilic, conjugated with polyphenolic material.
- Foam-positive proteins—10,000–15,000 Da, isoelectric point 5.5–8.0, hydrophobic, and associated with carbohydrates.

Production. Silica gel is produced by mixing sodium silicate and an acid, usually sulfuric acid, under carefully controlled conditions. This will yield polysilicic acid and then colloidal silica. These colloidal particles continue to react and form silica hydrogel (Fig. 8). The hydrogel is then washed and milled and has a moisture content of approximately 70%. By carefully monitoring the conditions during washing, the pore diameter and pore volume of the hydrogel used for protein adsorption can be controlled. Drying the hydrogel will yield a xerogel with a moisture content of roughly 5% (7,10,11) (Fig. 9).

Application. After fermentation, add to cold beer in-line during beer transfer or add in tank and allow to settle.

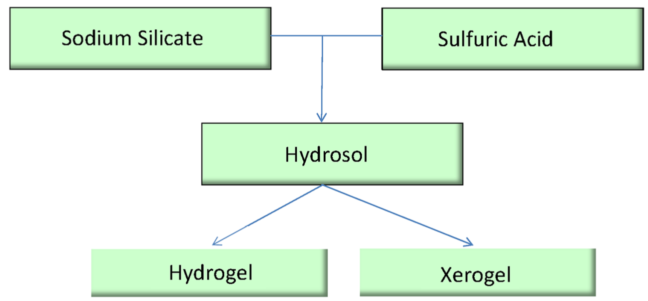

Figure 8. Silica hydrogel and xerogel production.

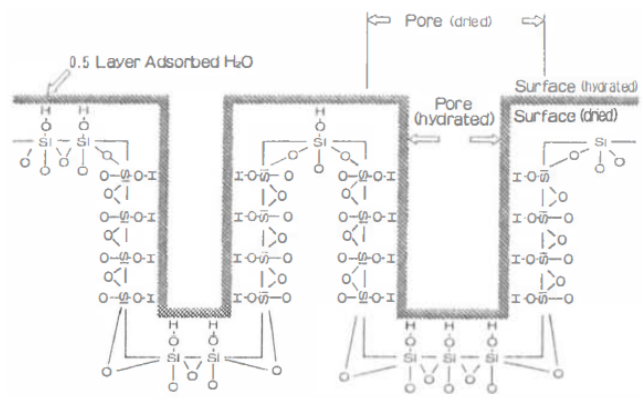

Figure 9. Surface of hydrogels. From Matsuzawa and Nagashima (13). Reproduced by permission.

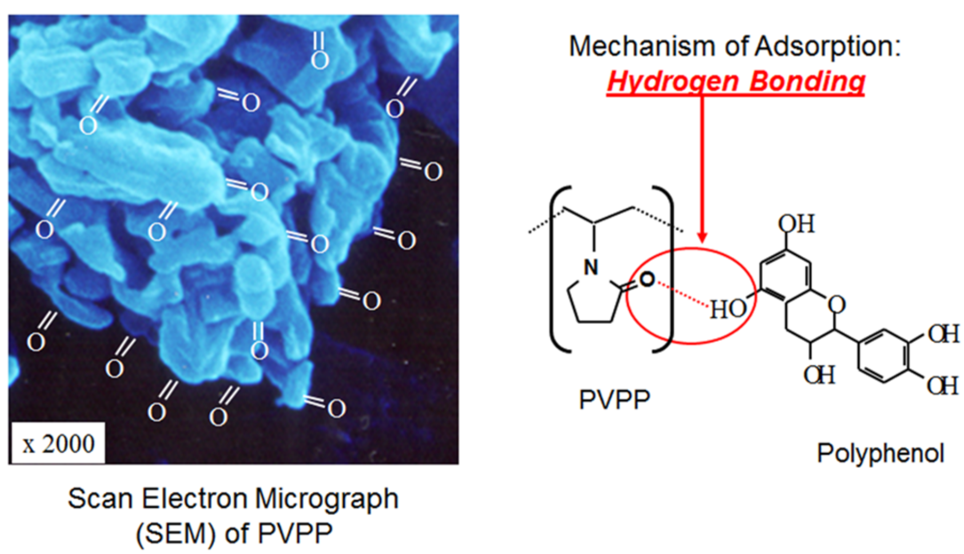

Figure 7. Close-up of polyvinylpolypyrrolidone (PVPP) and adsorption of PVPP and polyphenols via hydrogen bonding. Image courtesy of BASF SE.

Hydrogel

Particle size: ≈16 µm

Dose rate: Beer up to 65% malt

- 40–50 g/hL (≈10–12 lb/100 U.S. bbl)

Dose rate: Beer more than 65% malt

- 50–70 g/hL (≈12–17 lb/100 U.S. bbl)

Contact time: 20 min

Xerogel

Particle size: ≈12 µm

Dose rate: Beer up to 70% malt

- 25–40 g/hL (≈6–10 lb/100 U.S. bbl)

Dose rate: Beer more than 70% malt

- 40–60 g/hL (≈10–15 lb/100 U.S. bbl)

Contact time: 5 min

Preparation: Add 8–10% silica gel by weight in water in cold de-aerated water to allow for proper hydration and swelling. Apply CO_2 sparge if available.

Note: 8–10% is approximately equal to 1 lb of silica gel in 1 gal of de-aerated water.

Colloidal Silica

Particle size: ≈8 nm

Dose rate: 24–60 mL/bbl of beer

Contact time: ≈8 h

Preparation: Mix in de-aerated water. Apply CO_2 sparge if available.

Isinglass

Isinglass is a very pure form of collagen derived from the swim bladders of certain fish.

Background. It has a long history of use in the production of top-fermented beers, especially in the United Kingdom and for the production of cask beers.

The overall net charge of collagen in beer is positive at beer pH; the collagen is in a triple helix form with a net positive charge, but there are many sites of both positive and negative charge on the helices. This allows the isinglass to react with negatively charged yeast and negatively charged proteins in the beer, as well as positively charged proteins. Further, the triple helix structure traps other sediment as it falls through the vessel. It is often noted that isinglass also helps to improve foam stability of the beer, most likely owing to its ability to remove lipids and antifoam, if employed (17). It may also help with the action of both silica gel and PVPP. A freeze-dried product, ready to use, is also available to brewers.

Production. Isinglass is produced by soaking dried swim bladders of the fish in cold, dilute acid for up to six weeks, yielding collagen, which is ready for use. Further processing yields a more stable, freeze-dried product also available to brewers.

Application. Isinglass is added to beer any time after primary fermentation is complete or to the cask. It is fully compatible with silica gel, but PVPP should be added separately. It should also be added after the centrifuge is used in the process.

Dose rate: 1–5 g/hL (0.25–1.10 lb/100 U.S. bbl of beer).

Preparation. Mix at 0.5% w/v in cold de-aerated water, with a temperature less than 50°F. Apply CO_2 sparge if available.

Considerations

Through investigation and widespread use, it has been demonstrated that finings provide clear benefits for the brewer, in both process and quality (Table 1).

With use of finings, a common question is whether silica gel and PVPP can be mixed together and dosed into beer in order to stabilize the beer. It is often assumed that the two would only bind to one another and not remove the precursors to haze. As Ryder and Power (17) point out, the effect has been shown to be additive and even complementary; however, a slurry of silica gel and PVPP must be mixed vigorously to prevent aggregation of the particles.

It is important to note that under current U.S. regulations, the use of any silica or PVPP product requires filtration prior to packaging even if the beer meets a brewer's specification for clarity. Both the filter manufacturers and filter media suppliers are excellent resources to help brewers identify the best options for their specific plants and processes.

Finally, cold temperatures of the beer must be maintained for effectiveness of stabilizing (12,14).

The important point to remember is that finings are only part of the process. Specifically for haze and flavor stability, good brewing practices need to be used throughout the brewery by all employees.

Kunze (10) provides a good list as a starting point for good brewing practices, and the reader is encouraged to review the many publications that cover this broader subject.

Use of process aids without regard to any other good brewing practice will render their use almost completely worthless. Aside from these process aids, limited oxygen pick-up and cold storage temperatures should be first and foremost on every brewer's mind—after safety and efficiency, of course.

Table 1. Summary of Fining Options[a]

Stabilizer	Mechanism of action	Advantages	Disadvantages	Dosage range
Polyvinylpolypyrrolidone	Strong bonding to haze-active polyphenols via multiple bonding mechanisms.	Selective for haze-active polyphenols. Single use or regenerable.	Possible flavor loss if used in excess. Capital cost for regenerable filter plant.	5–40 g/hL (1.5–10.5 lb/bbl)
Silica hydrogel	Adsorbs haze-active proteins via hydrogen bonding.	Selective for haze-active proteins.	High usage rate.	30–100 g/hL (8–25 lb/bbl)
Silica xerogel	As hydrogel.	Selective for haze-active proteins. Lower usage rate than hydrogel.	Difficult to disperse. Reduced head retention if used in excess.	20–50 g/hL (5–13 lb/bbl)
Gallotannin (tannic acid)	Adsorbs haze-active proteins by hydrogen bonding.	Selective for haze-active proteins. Low usage rate.	Beer losses if used in tank. Flavor harshness if used in excess.	4–10 g/hL (1–2.5 lb/bbl)
Isinglass	Positive charge attracts negatively charged yeast cells.	Helps settle yeast and improve foam.	Short shelf life.	1–5 g/hL (0.25–1.25 lb/100 bbl)
Carrageenan	Negative charge attracts proteins.	Selective for haze-active proteins.	Some products may have marine aroma.	1–6 g/hL (0.25–1.5 lb/100 bbl)

[a] Adapted from Rehmanji et al. (16).

ACKNOWLEDGMENTS

Thank you to Dave Gusmer, Chris Atkinson, and Calvin Watkins for their support.

REFERENCES

1. Atkinson, C. Gusmer Enterprises brewing toolbox: Additives for clarification and stabilization. Internal communication.
2. Bamforth, C. W. (1999). Beer haze. J. Am. Soc. Brew. Chem. 57:81-90.
3. Dadic, M. (1984). Beer stability—A key to success in brewing. Tech. Q. Master Brew. Assoc. Am. 21:9-26.
4. Delcour, J. A., Van Loo, P., Moerman, E., and Vancraenenbroeck, R. (1988). Physico-chemical stabilisation of beer—Use of hydrolysable tannins for production of chill-proof beers. Tech. Q. Master Brew. Assoc. Am. 25:62-66.
5. Fernyhough, R., and Ryder, D. S. (1990). Customized silicas—A science for the future. Tech. Q. Master Brew. Assoc. Am. 27:94-102.
6. Fraser, D. M. (1964). Irish moss—Its brewing value. Tech. Q. Master Brew. Assoc. Am. 1:20-26.
7. Hough, J. S. (1994). Beer haze. In: The Biotechnology of Malting and Brewing, pp. 140-143. Cambridge University Press: Cambridge, U.K.
8. Hough, J. S. (1976). Silica hydro gels for chillproofing beer. Tech. Q. Master Brew. Assoc. Am 13:34-39.
9. Hough, J. S. Briggs, D. E., Stevens, R., and Young, T. W. (1982). Beer treatment. In: Malting and Brewing Science, Vol. 2, pp. 698-700. Chapman and Hall: London, U.K.
10. Kunze, W. (1997). Improving colloidal stability. In: Technology of Brewing and Malting, pp. 424-425. Transl. Trevor Wainwright. VLB: Berlin, Germany.
11. Leather, R. V. (1998). From field to firkin: An integrated approach to beer clarification and quality. J. Inst. Brew. 104:9-18.
12. Lewis, M. J. (2001). Personal communication.
13. Matsuzawa, K., and Nagashima, Y. (1990). A new hydrated silica gel for stabilization of beer. Tech. Q. Master Brew. Assoc. Am. 27:66-72.
14. Miedl, M., and Bamforth, C. (2004). The relative importance of temperature and time in the cold conditioning of beer. J. Am. Soc. Brew. Chem. 62:75-78.
15. O'Rourke, T. (2002). Colloidal stabilisation of beer. Brew. Int. 2:23-25.
16. Rehmanji, M., Gopal, C., and Mola, A. (2005). Beer stabilization technology—Clearly a matter of choice. Tech. Q. Master Brew. Assoc. Am. 42:332-338.
17. Ryder, D., and Power, J. (1995). Miscellaneous ingredients in aid of the process. In: Handbook of Brewing, pp. 204-235. W. Hardwick, ed. Marcel Dekker: New York, NY.
18. Siebert, K. J., Carrasco, A., and Lynn, P. Y. (1996). Formation of protein-polyphenol haze in beverages. J. Agric. Food Chem. 44:1997-2005.
19. Siebert, K. J., and Lynn, P. Y. (1997). Mechanisms of beer colloidal stabilization. J. Am. Soc. Brew. Chem. 55:73-78.
20. Steiner, E., Becker, T., and Gastl, M. (2010). Turbidity and haze formation in beer—Insights and overview. J. Inst. Brew. 116:360-368.
21. The Institute of Brewing. (1990). Haze protection and foam formation. In: An Introduction to Brewing Science and Technology, Series 2, Vol. 2. Malting, Wort Production, and Fermentation, pp. 77-85. The Institute of Brewing: London, U.K.
22. Watkins, C. (2014). Personal communication.