



Factors affecting the lifespan of cast refractory linings: a general overview

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Synopsis

Many factors, from engineering and design to supply, installation, and operation affect the service lifespan of cast refractory linings. If a shortcoming occurs at any of these stages, the lining lifespan can be drastically reduced. Although not every aspect that can affect a cast refractory lining's lifespan is outlined here, a few key points are highlighted, with an emphasis on the various installation parameters.

Keywords

cast linings, refractory lifespan, lining engineering and design, lining supply, lining installation, curing, dry-out.

Engineering and design

The engineering and design of any refractory lining is a complex discipline that requires a detailed knowledge of the process or operation, together with a knowledge of the available refractory materials and their properties. The success of a refractory lining is critical to a plant's operational performance and the safety of its personnel and surrounding environment. Therefore, optimal refractory selection for each specific application is of great importance.

Although not a performance criterion, economic decisions typically influence the final selection, and the most technically suited refractory material may not necessarily be chosen. The balance between economics and performance is often a trade-off for a particular lining design, even though it may not result in the longest lifespan in service.

The critical initial step for any refractory design is to understand the process metallurgy. Operating conditions such as temperature, pressure, chemical attack, thermal shock, abrasion, erosion, mechanical movement, vibration, and stress can all affect the life of a cast lining. For example, an operating temperature above the refractory maximum service temperature can weaken or melt the refractory, which may lead to a decrease in the lining life or failure of the lining. Thus, accurate knowledge of operating temperature and its variability is crucial information to have during the engineering and design of the lining.

Material selection must be based on a combination of the three major wear factors: mechanical, chemical, and thermal. These all induce different stresses in the lining and are all application-specific. In addition to the material type and selection, the engineering and design process for cast linings must also assess the type of anchoring system that will be implemented to support the refractories during operation.

Options such as the inclusion of stainless steel fibres in a cast lining may help increase the lining lifespan. Again, the inclusion of such a material must be carefully engineered and designed in order to ensure it is fit for purpose and will not lead to any detrimental effects. The addition of stainless steel fibres can help increase the spalling resistance of cast linings through the increase in tensile strength that the fibres offer. Consequently, cast linings often utilize stainless steel fibres when mechanical stresses are important or when a lining is subject to thermal cycling or repeated thermal shocks.

There is a fine balance in determining the proportion of stainless steel fibres required. Typically, the fibre addition ranges between 2–4% by weight. Although the fibres add to the lining's mechanical strength and thermal shock resistance, additions above 3% may have a detrimental influence on the mixing characteristics of the castable, as well as its fluidity. Fibre balling may occur, where the fibres tend to clump together and form a ball within the cast lining. If left in a castable lining as such, the balls of fibre may lead to a decrease in the lining life or even failure in some severe cases.

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The success of a refractory lining when installed in a vertical or overhead position is dependent on the success of the designed anchoring system. A refractory anchor, like the refractory material selection, must be fit for purpose. The selection criteria for a given anchoring system can be as complex as for the refractory material itself, but are often neglected in the engineering and design phase. The anchor's length, diameter, spacing, and orientation are all critical factors that must be closely examined. The number of anchors to be used is dependent on the operating conditions, the refractory materials used, and the lining thickness. The choice of anchor material, shape, number, and size all have a significant impact on the cast refractory lining lifespan.

The installation of the anchoring system is also critical for the lining life. The anchor installation often involves welding a heat-resistant anchor to a carbon steel shell, and it is therefore imperative that a detailed welding procedure is prepared as part of the design phase. To ensure the anchoring system is fit for purpose, the welding procedure should include mechanical testing, chemical testing, and metallographic examination, with the chemical testing being of the utmost importance. The chemical test will confirm that the weld material will perform as well as the anchor material itself.

Anchors can fail due a number of different situations that commonly arise in refractory linings. For example, expansion/contraction differences between the anchor material and the refractory materials can induce excessive stresses in the lining that may reduce the lining life. Errors in the anchor component design, manufacture, and installation can all lead to a decreased lifespan or even failure of the refractory lining.

A common error during the engineering of a refractory lining occurs when refractory material data sheet values are used for critical lining stability calculations involving the three major wear factors. Using the incorrect or average material property data may lead to critical flaws in the lining design, and result in a reduced lining lifespan. It is good practice to use extreme minimum and maximum property values in order to account for worst-case scenarios when engineering and designing a refractory lining.

Supply

The material data sheet values are often used for engineering calculations and refractory lining designs. However, a data sheet is not a specification, and often refers to 'typical' technical properties, in that it shows the average chemical and physical properties for a large number of production batches. All refractory materials will vary in both chemical composition and physical properties from batch to batch and even within a batch. It is the responsibility of the refractory manufacturer to control the variations within acceptable limits. The consistency of the mix will also play a role in the property and composition variability that may be experienced. In essence, the challenge for the manufacturer lies in producing a consistent product repeatedly to ensure that the design lining life can be achieved when in operation.

In general, the data sheets are based on tests used by the manufacturer for quality assurance purposes and are not intended to be used for determining the suitability of the product for a specific application. Therefore, the engineer or

designer must have an intimate knowledge of the refractory materials being selected for any given application in order to minimize the amount of misleading information being extracted for a lining design.

Contrary to general belief, the chemical composition of a refractory material may not be the most important selection criterion as a chemical analysis alone gives only compositional information. It does not allow for the evaluation of properties such as volume stability at high temperatures or the ability of the material to withstand stress, slagging, or spalling.

The pore size distribution is a very important parameter. Like many other aspects of cast linings, the pore size distribution must be balanced between the greater mechanical strength and increased resistance to chemical attack conferred by a lower porosity and the increased thermal shock resistance that comes with a higher porosity. Pore size distribution also affects the resistance of the material to slag attack and, in turn, the lifespan of the material.

Cold crushing strength (CCS) values listed on material manufacturers' data sheets can also be misleading if not carefully examined. Cold or room-temperature measurements cannot be used directly to predict how the material will perform in service. In addition, different CCS results for the same material can be obtained simply by using different test procedures. CCS does, however, give a good indication of the degree of bond formation during production.

Apart from material properties, other important factors to consider in the supply of the material include packaging, storage, and shelf life. As with most refractory materials, castables should be stored in dry, well-ventilated areas and held off the floor, most typically on pallets. This is usually not a concern at the refractory manufacturer's facilities; however, adequate storage facilities are rarely found onsite prior to installation. If the castable materials are to be stored outside, the bags must be protected from rain or dripping water by a fixed waterproof cover. If the bags are further protected by plastic sheeting, sufficient ventilation should be available to prevent water from condensing on the bags. Although not always possible, storage in high humidity areas should be avoided.

The maximum stacking height for castables is often no more than three pallets high, and should be reduced to two pallets high when storing lightweight castables. Packing the castables too high can lead to the consolidation and caking of the material in the bottom rows of the bottom pallet.

Castable materials tend to have a nominal shelf life ranging from 6 to 12 months, depending on the material type. Products that are older than the shelf life should be checked by the manufacturer for setting properties, moisture demand, and mechanical strength prior to use. Increased setting times can indicate aging, but more importantly, aging can lead to a reduction in the castable strength and in turn the lining lifespan.

Due to the variability in the different materials within and across the various suppliers it is critical that the guidelines and specifications for refractory installation are followed carefully. The installation procedures and specifications written by the refractory manufacturer are intended to ensure the material will perform as per design in service. Although the procedures and specifications are often very detailed, skill and expertise are required during the installation stage.

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Installation

There are many factors during installation that can affect the lifespan of a cast refractory lining. It is imperative that good refractory practices, techniques, skill, knowledge, and experience are implemented by qualified installation personnel.

The first important aspect in the installation process is to ensure that all the equipment that will be used for the installation is clean and free of all foreign debris and contaminants. The mixers and vibrators should be regularly cleaned. Depending on the type of debris or contaminants present, flash setting can occur, which can compromise the lining life.

One of the major factors at the installation stage that contribute to a cast lining's lifespan is the water addition. The amount of water added to the castable affects the properties more than any other factor, and must be measured accurately and according to the material manufacturer's specification. Adding too much water may dilute the binder and weaken the mix, but also leads to a floating of the cement fines to the cast surface upon vibration. Too little water prevents proper vibration and the ability of the cast to reach its design density.

The water temperature also plays an important role in the castable lifespan. Cold water tends to delay the setting times, while hot water tends to accelerate the set and may even lead to flash setting in the mixer. The cleanliness of the water also plays an important role in the quality of the cast lining, and only potable water should be used when mixing the castable materials.

Although the environment on site may make it difficult to achieve ideal installation conditions, steps can be taken to counteract the detrimental effects. For example, if the weather is cold, warm water should be used (and *vice versa*) to ensure the mix temperature is roughly at room temperature upon casting.

Stainless steel fibre additions, if required, should be added to the castable after all the refractory and water has been added to the mixer. In order to help minimize or prevent fibre balling, the fibres should be sprinkled over the mix in order to loosen and separate the individual fibres. It is important to note that in castables that already contain fibres, the addition of water should be based on the weight of the powder and not the weight of the bag. It is also important to note that although the addition of the stainless steel fibres may lower the fluidity of the mix, no extra water needs to be added to compensate for this loss of fluidity.

The anchoring system must be properly installed so that it behaves exactly as the design intended. Details such as the anchor spacing and the anchor orientation must be strictly adhered to in order to prevent failures in the lining. Shear or stress concentrations can be formed within the lining through the incorrect anchor spacing and orientation on installation. It is also important to ensure that the metal anchors have plastic caps to compensate for linear thermal expansion and for the difference in expansion coefficients between the anchor and the refractory material. In order to further enhance the anchoring system performance, it is also good practice to paint the refractory anchor with a bitumen paint to accommodate any radial expansion throughout the anchor diameter and to allow for minimal movement of the lining without inducing additional stresses.

The mixing time must also be respected. Excessive mixing generates heat and speeds up the setting time, and insufficient mixing can result in a non-homogeneous batch, both of which can lead to a reduction in the cast lining strength. Generally, depending on the material, conventional castables are mixed for 2 to 5 minutes and start to set within 20 minutes of being mixed, leaving 20 minutes for the transportation of the material from the mixer to the casting area for installation. The mixer should therefore be placed as close to the casting area as possible, and a single batch should not contain more material than can be installed within 20 minutes. This 20 minute time span is often referred to as the working time of the castable material.

Oiling of the formers prior to the start of installation is good practice. Not only does this allow for easy removal, but it also helps prevent moisture loss during setting. The former material must be carefully chosen to ensure that no moisture is drawn from the castable into the formwork during setting and curing.

It is essential that the refractory castable be vibrated accordingly upon casting. This not only ensures that the castable flows to all areas of the cast, but also aids in the removal of air pockets and air bubbles, which in turn increases the castable density and strength. A balance must be achieved, as over-vibration can lead to the segregation of the components (water from the mix) and weaken the lining, thus reducing its lifespan. It is imperative that at no point during the curing process should the casting be moved, shaken, or vibrated as these will all interrupt the bonding process. If the bonding process is interrupted, the final cast product will most likely exhibit a reduction in ultimate strength.

The final vibrated material will have a wet appearance and the rising of the air bubbles to the surface will have ceased. The movement and removal of the vibrator through and out of the castable should be done with skill and care. If the vibrator is forced through the castable or removed too quickly, holes, channels, and/or pockets of air can remain or form in the lining which can, in turn, lead to a reduction in lining life or to lining failure.

Although an aesthetically pleasing finish is appealing to many clients, excess surface troweling should be avoided when finishing the exposed surface of the casting to the necessary shape or level. Trowelling of the surface draws the water, which carries cement fines, to the surface of the cast. This produces a cement-rich segregate material on the cast surface that is easily dislodged by heating and cooling cycles. In addition, it seals the surface and can impede the escape of moisture during dry-out.

Curing times and temperatures are also important to the cast lining life. It is important to allow for a 12-24 hour curing time to allow for the full hydration of the calcium aluminate binder. Loss of water from the surface of the cast before the cement is fully hydrated results in a weaker cast. If the material dries out before the cement has had time to fully hydrate, the castable strength will be reduced significantly.

At no point during the casting, curing, or drying time should the castable be subjected to freezing temperatures. If the castable freezes before the hydraulic set is completed, the material's ultimate strength can be decreased by more than 50%. Conversely, at high temperatures, the setting time is

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drastically reduced leading to the incomplete formation of the required hydrated cement bonds that contribute to the cast's ultimate strength.

The most critical factor that can affect the cast refractory lining's lifespan is the refractory dry-out. This is the last stage in the installation process, and carries over into the start of operation and production during the commissioning phase. The objective of the carry-over is to bring the refractory lining to a condition suitable to commence operation.

Unfortunately, it is not possible to recommend a standard dry-out schedule to meet all conditions. Due to the variability of the products, their water contents, and their final desired properties it is crucial that the dry-out procedure, also known as the heat-up schedule, is obtained from the refractory manufacturer for that particular material and that it is followed strictly.

The main mode of failure during the refractory dry-out is spalling, which is often the result of excessive pressurization of entrapped steam that forms upon heating the lining. In general, if the refractories are heated up too rapidly, steam will form quicker than it can escape, resulting in cracking and in worse cases, spalling and explosion spalling as the internal steam pressure exceeds the mechanical strength of the castable. Also, if the refractories are heated in such a way that the surface of the cast lining bakes, an impenetrable crust can form that traps the steam within the cast. In such instances spalling is inevitable.

Cast linings contain two different forms of water, known as free water and combined water. The free water in the cast remains in the pores and does not react with the other components in the castable. Free water can be driven off at a temperature just above the boiling point of water at 100°C. The combined water, however, is usually present in the hydrated compounds of the cement and can be removed at temperatures ranging between 150°C to 650°C, depending on the material.

Typically, once the curing process is complete, the dry-out is commenced by slowly increasing the cast lining temperature by 20–30°C per hour from room temperature to approximately 110°C, and holding for 1 hour for every 25 mm of lining thickness. After the first hold is complete, the 20–30°C incremental hourly temperature increase is resumed until approximately 350°C, where the second hold takes place. Depending on the castable material, a third hold may also be required. The key is to increase by 20–30°C every hour until the hold points and after each hold. Once the last hold is complete, the lining temperature can be increased at a rate of 50°C per hour until the required working temperature for commissioning is achieved. Note that any castable can be heated up at a slower than recommended rate, but never at a faster one.

In some instances, in order to allow for a more aggressive dry-out schedule, while practicing extreme caution, additions of low melting temperature fibres such as polypropylene fibres, for example, can be added to the mix. As the lining is heated up, the additional fibres burn out and form permeable paths for vapour to escape into the atmosphere, thereby relieving the internal lining pressure and the potential for spalling.

The key when drying out the refractory lining is to ensure all the steam has a safe exit path from the lining. As a simple

and generic guideline, if at any time during the dry-out steam is witnessed the temperature should be held until no more steam is being generated. It should be kept in mind that the dry-out sequence and generalizations mentioned here should not be replicated for any specific lining dry-out. Rather, the manufacturer's heat-up schedule should be strictly followed.

When drying out the refractory lining it is also crucial to keep in mind that a temperature gradient will exist in the cast lining between the hot and the cold faces. In order to properly dry out castable refractories, thermocouples should be placed at both the hot and the cold faces of the lining. This ensures that once the lining-specific hold temperatures are achieved at the cold face, the free and combined water have been removed from the entire lining. A key component of a good dry-out is to minimize this gradient as much as possible, inherently reducing the thermal stresses induced in the lining and increasing the lining lifespan towards its design life.

Important heating characteristics include good temperature homogeneity, control of heating and cooling rates, and effective heat transfer. One of the worst-case scenarios in drying out occurs when one or all of the dry-out burners fail. All precautions should be taken to ensure that once the refractory dry-out commences it is not interrupted in any way. If such a situation does occur, every attempt must be made to keep the lining warm. When cooling down cannot be avoided it must be done very carefully, and reheating should be carried out as per the original heat-up schedule. The temperature reversal that is experienced in losing a burner during the dry-out leads to a reversal of the steam direction back through the lining, but with an extremely explosive force.

Although the main information in this dry-out section was based on a single lining layer, the general guidelines listed here can also be applied to multi-layer linings with an insulation castable at the cold face. Due to the fact that the insulation castable has a much higher water content, the drying out procedure must remove the water from the insulating lining without damaging the hot face castable. In addition, with a lining that is heavily insulated, the temperature in the dense hot face material rises more rapidly and a slower heat up is required. The dry-out for a multilayer lining can be done in a number of ways. Drying out the installation slowly, drying out the insulation lining before installing the hot face castable, and venting the steel shell (creating weep holes) so that moisture can escape from the cold face instead of the hot face are just some examples of the techniques that can be employed. In instances where none of these options are possible, such as for pressure vessels, a matrix of 3 mm diameter holes through the hot face castable spaced every 30 cm can be considered. These holes will allow the moisture to escape from the insulation through the hot face lining without compromising its integrity.

Unfortunately, as was the case for the material selection and design, economic considerations often dictate the speed at which a refractory lining is dried out and full production reached. This is not only due to the costs associated with the dry-out, but more a result of the lost production time (anywhere from 36 hours upwards) entailed in order to carefully dry out the refractory lining. What must always be kept in mind are the long-term economic losses that can result from the loss in production due to a failed lining that was not dried out properly.

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Operation

The commissioning of the refractory lining is also extremely important to the lining's lifespan. In many cases the dry-out is fast-tracked and the operation started in order to reach full production as quickly as possible. Such decisions are often made by personnel that have little knowledge of the effect on the refractory lining lifespan. Typically, the end user rarely appreciates the amount of effort that goes into the lining design, supply, and installation specifications and procedures, and the importance of these for the final refractory life.

It is evident that the operating conditions that the lining experiences are critical to its life. Refractory failures can result from the most minor changes in the process operational variables. The difficulty comes in trying to control the process operational parameters closely to those on which the lining was developed.

If the lining is engineered and designed for a certain set of operating parameters and conditions and those parameters and conditions change, so should the refractory material design to ensure that the lining is fit for purpose. The conditions that were specified originally in order to accurately engineer and design the lining are no longer the conditions

the installed refractory lining is experiencing, which leads to a decreased lifespan for the installed cast lining and in many cases failure of the lining.

Conclusion

There are a number of factors that can affect the lifespan of cast refractory lining, many of which are not mentioned in this paper. A successful lining requires a fine balance of many factors, as well as an interdisciplinary attitude by all parties involved in the lining design, supply, installation, and end use. A complex combination of knowledge and skills acquired through education and training by all parties involved is required in order to ensure that a cast refractory lining reaches its full design lifespan. In addition, stringent quality control procedures and checks during every stage of the refractory lining, from conception to maintenance, should be implemented to ensure a maximum-life refractory lining installation.

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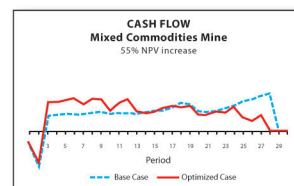
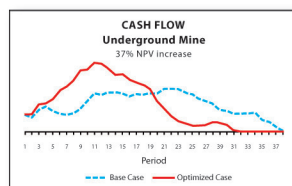
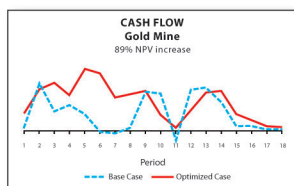
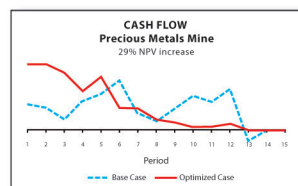
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