Specification and Design of Enclosures for Gas Treatment

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Abstract

The paper draws on experience within the Australian grain industry to review the state-of-the art in relation to the design and specification of gastight storages, concentrating principally on its application to the storage of grain in bulk.

Problems associated with sealing different types of storages are discussed and commonly used sealing materials and methods are reviewed. The paper also covers in some detail points which should be considered when preparing specifications for sealing work, including types of contract and the selection and specification of sealing materials. The paper draws attention to current deficiencies in test standards and acceptance criteria for many commonly used coatings.

The paper also reviews current gastightness testing procedures and commonly used methods of air leak detection.

SINCE the inception of gastight storages for fumigation treatment of grain in the 1960s, the art of gas-sealing has evolved into a well controlled 'science', and it is now almost standard practice in Australia for new storages to be built to gastightness specifications. Significant efforts have also been made to seal numerous older storages in order to gain the benefits, both financial and operational, that sealed storages can offer.

The cost of gas-sealing new storages need not be high if the design is detailed to facilitate sealing. In fact, for some types of structures the cost can be negligible. The cost of retro-sealing older structures not designed for gas-sealing can, however, be significant. In both cases, the cost of sealing will be largely dependent on the detailed design of the storage structure while the success of the sealing will be dependent to a large extent on the appropriateness of the specification relating to its application.

This paper concentrates on design details for new structures that facilitate sealing, and on appropriate materials and specifications for achieving satisfactory sealing of both new and old structures.

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Sealable Storage Types

Virtually any type of grain storage can be made gastight. As noted in other papers in these proceedings, bag stacks are routinely gas-sealed in China and some Southeast Asian countries by fully enveloping them in polythene sheets which are carefully sealed at all joints either by heat welding or by mechanical fastening (Fig. 1).

Bulk storages can be similarly sealed; for instance as is commonly practiced in Australia where bulk grain in bunker storages is encapsulated within reinforced PVC or polyethylene covers which are mechanically sealed together at joints and around the periphery.

With permanent bulk storages it is necessary to seal the storage structure itself. Almost any storage structure can be sealed, the cost depending to a large extent on the type of structure and its design detail.

Fig. 1. Sealed bag stack (China 1986).

In Australia, grain storages are normally constructed from either concrete or steel. Vertical silos and horizontal sheds built from these materials are routinely sealed for fumigation. There has been little work done in the sealing of timber or masonry storages which are rarely found in Australia. There is, however, little doubt that the materials and methods that have been developed for sealing steel and concrete structures could equally well be used for sealing timber and masonry storages.

Design of New Storages for Ease of Sealing

This section covers design aspects for new storage structures to facilitate sealing. Section 4 looks at the design of doors and other apertures to facilitate routine sealing for fumigation.

Reinforced Concrete Silos

Gastight concrete silos (Fig. 2) have been routinely constructed in Australia over the last 20 years and most have retained their gastightness throughout prolonged usage. A good example is a group of twelve 2600-tonne bins built in Brisbane, Queensland in 1968 which have been filled and emptied on average around 25 times per year or, say, a total of 500 times to date. The bins are of reinforced concrete slip form construction, with cast-in-place conical concrete floors and roofs. They have retained a high standard of gastightness without the need for any surface coating or treatment.Indeed, this applies to all of the 150 or so concrete silos, varying from 1000–7000 tonnes capacity, that have been built in Queensland over the last 20 years (Newman 1987).

The following basic principles were established in Queensland for the achievement of gastightness in reinforced concrete silos:

- Bins should be independent rather than interconnected (Fig. 3). Interconnection of bins results in nonuniform expansion of the walls which can cause vertical cracking. Fitting of gastight roofs to interconnected bins is also much more difficult. It can be added that independent bins are easier and generally less costly to build than interconnected ones.

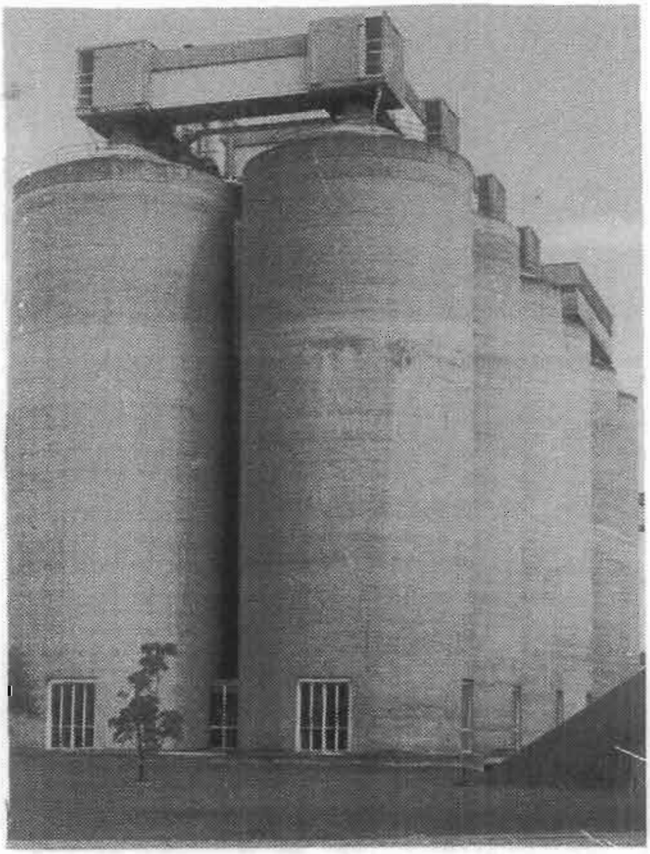


Fig. 2. Gastight concrete silos at Pinkenba, Queensland, Australia.

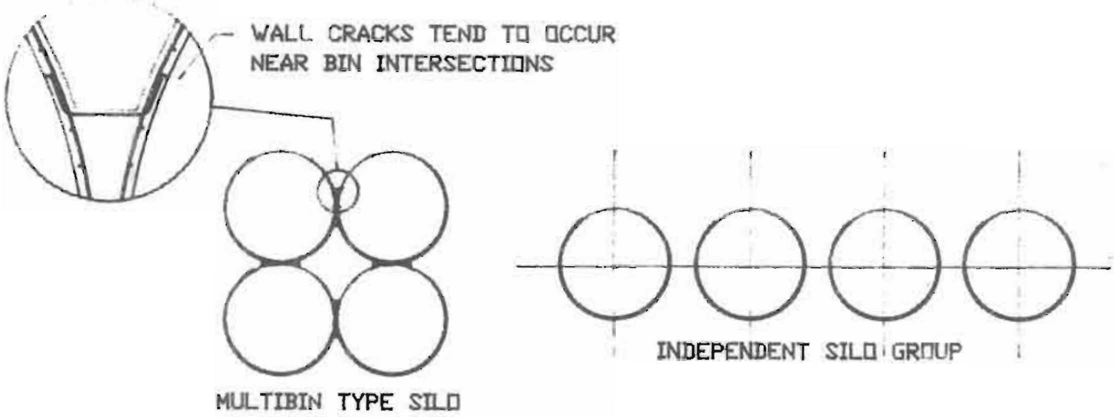


Fig. 3. Independent silos are easier to make gastight than interconnected bins.

• Sufficient reinforcing steel must be incorporated into the bin walls. Tensile stresses in the horizontal reinforcement should not exceed 135 MPa under peak pressures (normally during outloading). Higher stresses should not be permitted even if high strength steels are used, since cracks will become unacceptably wide. Single reinforcement (i.e. a single mat of horizontal and vertical reinforcement) centrally placed has proven satisfactory in bins of up to 3000 tonnes capacity. Nevertheless, double reinforcement (separate mats adjacent to each face) results in a very significant increase in wall stiffness, ensuring greater resilience against uneven loading. Double reinforcement is to be strongly recommended in new constructions, especially in silos of over 3000 tonnes capacity or in silos which are to be eccentrically loaded or unloaded. Typical features of gastight concrete silos are illustrated in Figure 4.

• High standards of quality control and supervision during construction are essential to ensure that:

- placement of reinforcing steel is correct;
- the specified cement content is used in the concrete;
- maximum water:cement ratio is not exceeded (0.55 recommended for most environments);
- 'cold' joints do not occur during construction or, if they do, that they are properly cleaned and treated to ensure a good bond;
- concrete temperature is controlled before and after pouring;
- curing of the concrete surfaces is properly carried out; and
- good construction practices are rigorously followed.

• The effects of eccentric filling and emptying of a silo should not be under-estimated. Off-centre emptying in particular can create major grain pressure differentials around the bin circumference (Fig. 5). These can result in distortion of the bin wall and thus a risk of vertical cracking (Gorenc et al. 1986).

A detailed discussion of eccentric loadings is beyond the scope of this paper. There are, however, a few matters that should be attended to in order to minimise loss of gastightness when eccentric loading and unloading is liable to occur.

• Use double reinforcement in the bin wall as outlined earlier, to increase resistance to distortion and cracking (Wood 1983).

• The bin wall should be rigidly connected to the foundation or bottom ring-beam by reinforcing steel (Fig. 6). This will substantially increase the stiffness of the wall and also simplify sealing of the joint. The sealing of such joints is most readily achieved by a PVC water-stop cast into the concrete.

• Use of the bin roof as a stiffening member will also add significantly to the rigidity of the bin walls. A stiffening member has itself to be very rigid, and a concrete roof cast in place is likely to be the most appropriate form of construction to give adequate stiffness. While there are many circumstances in which it is cheaper to construct steel or precast concrete roofs for concrete wall silos, a stiffening action is harder to achieve by this course and consequent movement of the wall below the roof can occur making a gas seal difficult to maintain (Fig. 7).

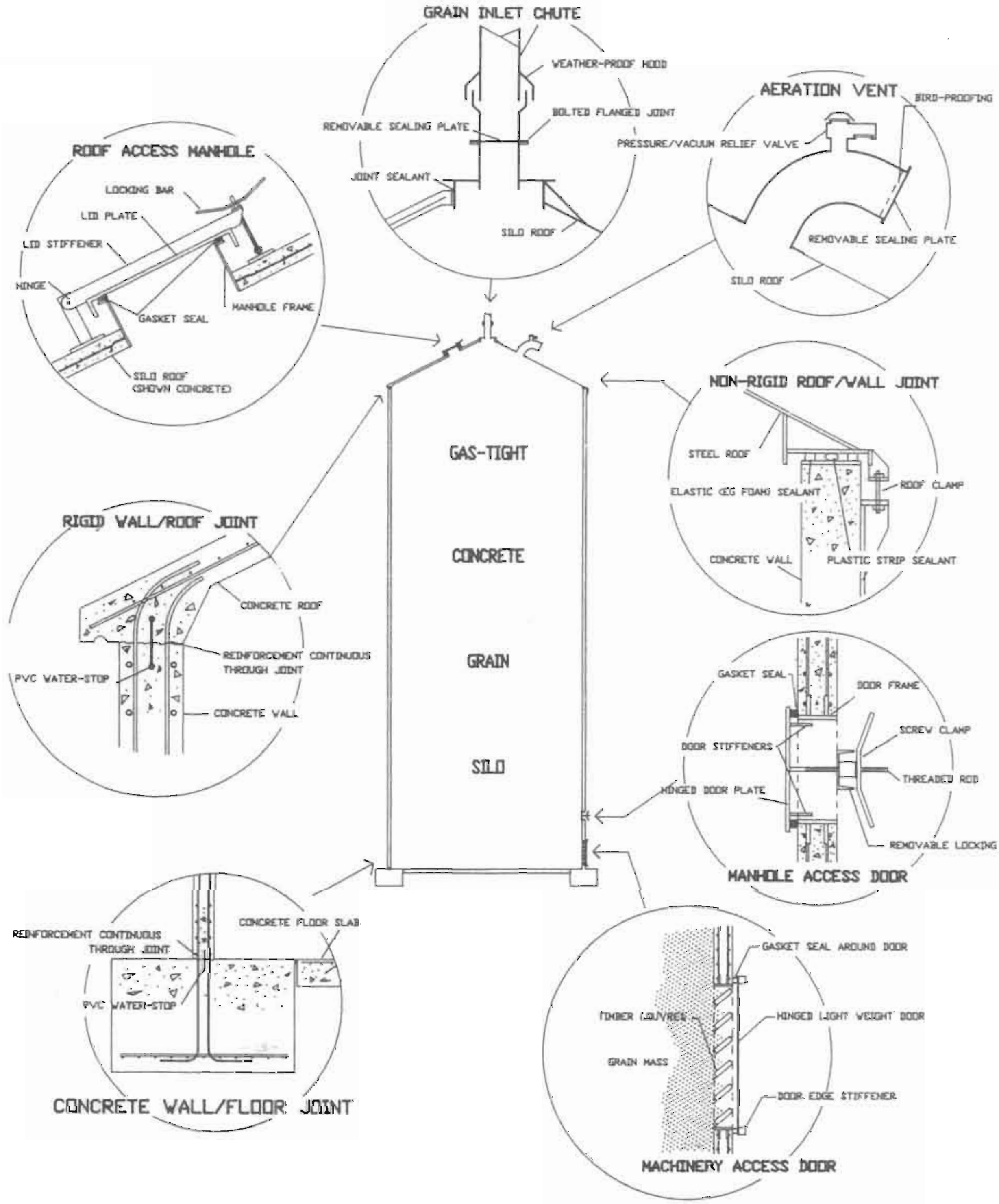


Fig. 4. Typical features of a gastight concrete silo.

In considering sealed concrete silos, the potential use of carbon dioxide for grain disinfestation needs to be considered: the chemical reactivity between this gas and concrete can pose both short- and longer term problems. Through the process of 'carbonation', CO_2 converts calcium hydroxide in the cement matrix to calcium carbonate. This results in a potential long-term reduction in corrosion protection to reinforcing steel, caused by the neutralisation of the alkaline component of the concrete. A very rapid rate of gas 'loss' can also occur in a new concrete structure which is exposed to CO_2, due to the rapid uptake of gas that can take place. Extra CO_2 must be added to make up for this loss and adequate pressure

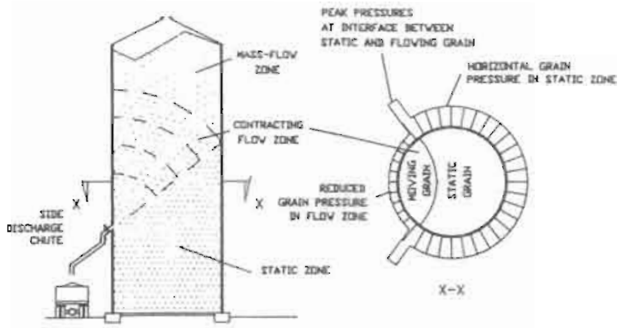


Fig. 5. Grain pressure differentials resulting from eccentric discharge of a vertical silo.

relief needs to be provided to guard against structural damage resulting from the high negative pressures that can occur inside the storage as the reaction takes place (Banks and McCabe 1988).

Welded Steel Silos

Welded steel silos are inherently gastight and require no special design considerations in relation to gas sealing. An exception applies to silos with concrete floors, where the joint between wall and floor has to be made gastight (Fig. 8). Such joints usually occur between the steel wall and concrete foundation or stub wall and can be sealed with a wide variety of sealant types. The choice of sealant may depend on whether or not movement between the steel wall and concrete foundation is to be permitted, but either way it is unlikely that an adequate seal would prove difficult to achieve.

Bolted Light Gauge Steel Silos

While heavy gauge bolted steel silos should not present difficulties in sealing, light gauge bolted bins have generally not been easy to seal and, indeed, until recent times were often considered unsealable due to the amount of movement that occurs in the wall joints and at bolt fixings during filling and emptying.

Recent development work in Australia has resulted in designs for light gauge steel silos that can be sealed to a high level of gastightness. One design uses adhesive cellular foam sealing strips as gaskets between the corrugated steel sheets forming the walls. Also, special fabric-reinforced washers that remain stable under high compressive forces are used under all bolt heads thereby sealing the bolt holes.

The conical roof of this type of structure also differs from most standard light gauge bins; a rigid framework of radial beams (rafters) supports light gauge steel roofing segments. Excessive movement of the roof sheeting is thus prevented, allowing joint sealants to remain intact and effective.

Another form of light gauge bolted steel silo that has been successfully gas sealed incorporates a light-weight skeletal frame onto which the internal walls and external roof sheeting are attached (Fig. 9). Despite the large number of laps, joints, fastenings, and complex interfaces, silos such as these can be made gastight provided care and attention is given to detail during design and construction.

Horizontal Sheds and Similar Structures

Horizontal bulk-storage sheds in Australia are usually steel-framed with corrugated steel sheeting forming the walls and roof, although the load-bearing walls are sometimes made of concrete.

Sealing of such structures is made easier if the design is carefully detailed to facilitate the application of sealants.

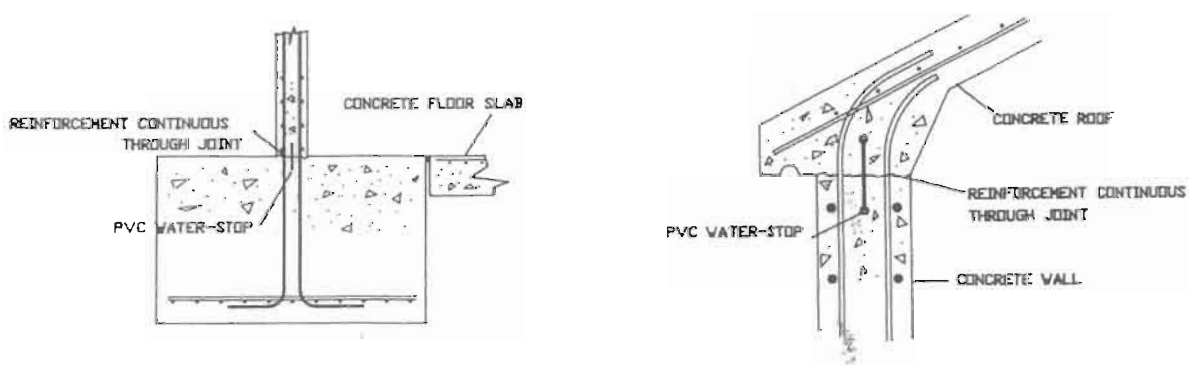


Fig. 6. Detail of typical rigid connections at the top and bottom of a concrete silo wall. Note PVC water stop in gas sealing joint.

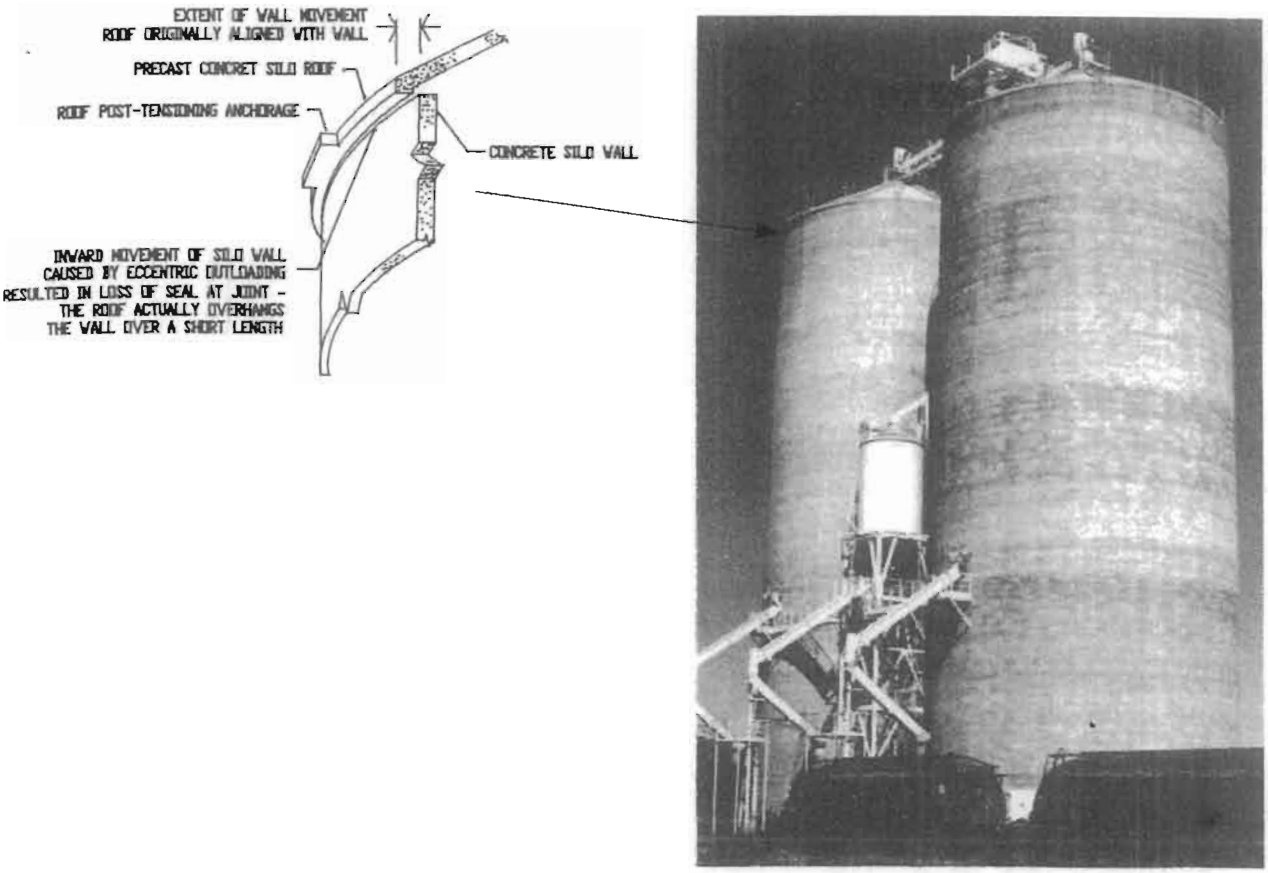


Fig. 7. Example of loss of seal caused by eccentric discharge through side chutes in concrete silos.

Principle design requirements are as follows:

- Gaps between sections of sheeting (e.g. between roof and wall sheeting) should be kept to a minimum and bridged with steel flashings.
- Deflections under load (either from grain load, wind-load, or static air pressure differentials) should be kept to a minimum by good structural design and by use of adequate fastenings for attaching and joining the wall or roof sheeting to the structural framework. The number of fastenings may exceed that required to resist normal wind loads.

Regardless of the care a designer takes, many of the joints in such structures will need sealing. In particular, joints will occur between corrugated sheets where they overlap either at their sides or ends. Gaps will also occur wherever corrugated sheets are attached to flat (uncorrugated) structural members or flashings. However, sealing of such joints or gaps is not difficult, though the work has to be done with great thoroughness.

Preformed foam 'corrugation closures' are available for most standard corrugation profiles, though an application of sealant coating over

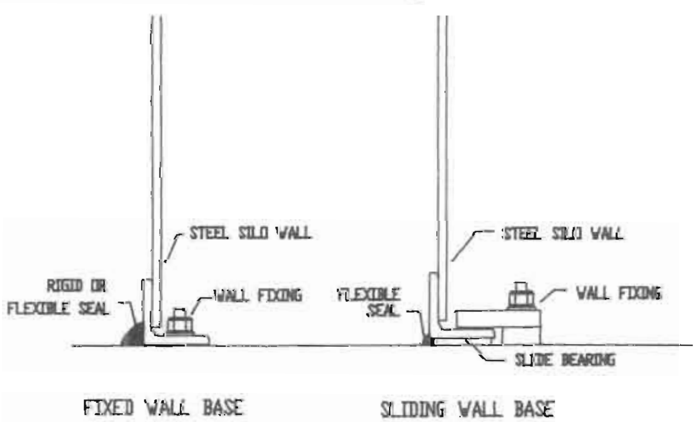


Fig. 8. Typical connections between walls and footings of steel silos.

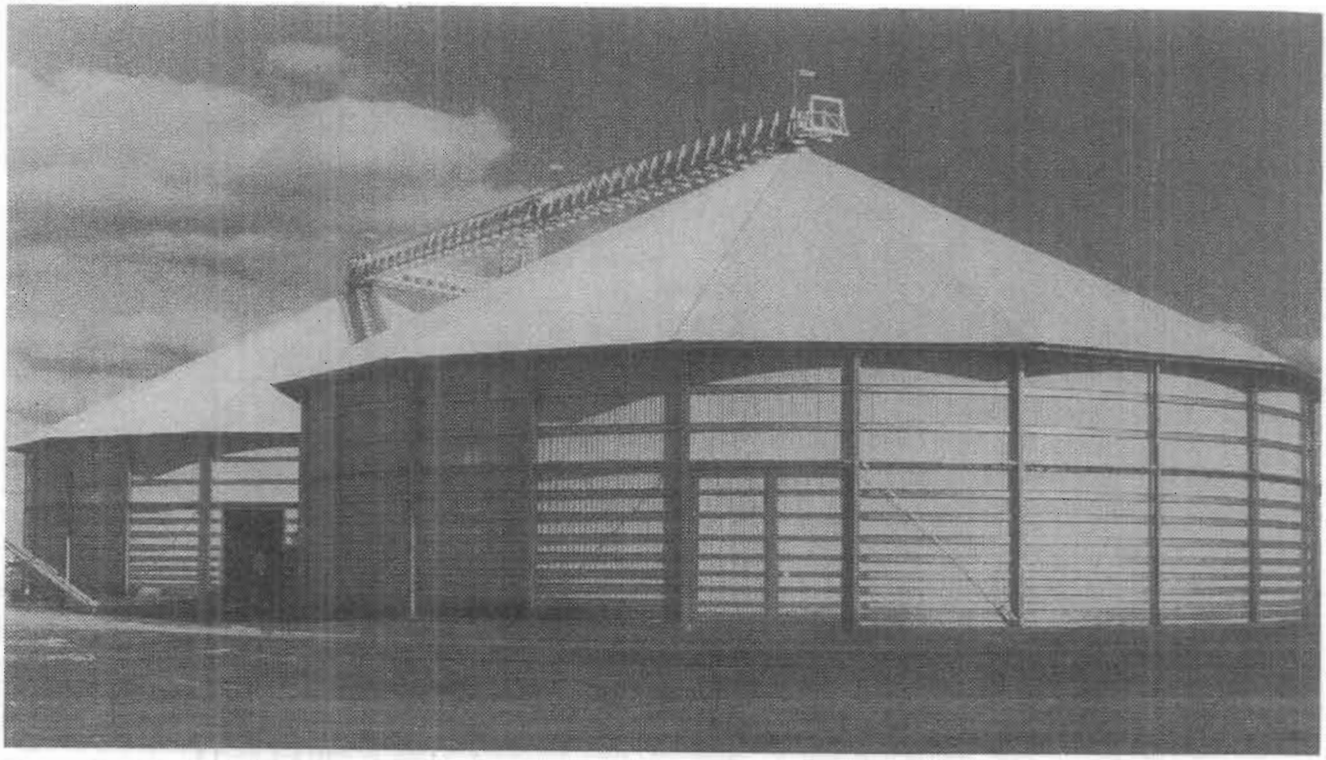


Fig. 9. Gastight bolted light gauge steel silo.

them is still necessary to ensure gastightness. Alternatively, sprayed polyurethane foam (Fig. 10) is often applied to bridge over corrugation gaps, though once again a sealant coating is normally applied over the top.

Sealing of laps between corrugated sheets can be done in a number of ways. These include:

- Applying silicone sealant inside each joint as the sheets are set in place and fixed together. Since silicone 'sets' relatively quickly, successful implementation of this method requires conscientious roof sheeters working under close supervision.
- Injecting acrylic sealant paint into the joints after placement of the sheets. To be effective, this method requires releasing the fixings to inject the sealant into the joints and refixing again immediately afterwards.
- Applying silicone sealant or sealant coating externally over the joints.
- Applying a preformed cellular foam sealing strip between sheets before they are fixed. To be effective this requires extra fastenings to ensure that the foam gasket is maintained in compression along the full length of the joint.

It is not uncommon for a combination of these treatments to be applied; for instance, lap joints may be externally coated with acrylic sealant after being pre-sealed with silicone or foam sealing strips.

Particular care needs to be taken at the interface between roof and walls of such structures. Whilst side laps between sheets may be sealed to prevent gas passing through them, the sealant will not normally prevent gas passing along them. If this leakage path is not interrupted at the wall/roof interface, such joints will form 'tunnels' for gas to leak from (Fig. 11(a)). It is thus important to seal across the full width of all lap joints at roof/wall interfaces and to provide continuity between these seals and the seal between the roof and wall. A similar situation occurs at ridge cappings which require blocking off at their ends (Fig. 11(b)).

Pressure Venting

It is important to recognise that a gastight structure will be subject to internal variations in pressure relative to that of the external atmosphere. Pressure differentials can arise from a number of causes; for instance, variations in atmospheric pressure, wind effects, and air displacement during filling or emptying of the storage.

Adequate pressure-relief venting of a sealed storage is essential to avoid excessive pressure differentials that might cause structural damage. Vents must be large enough to allow air to pass into or out of the structure at a rapid enough

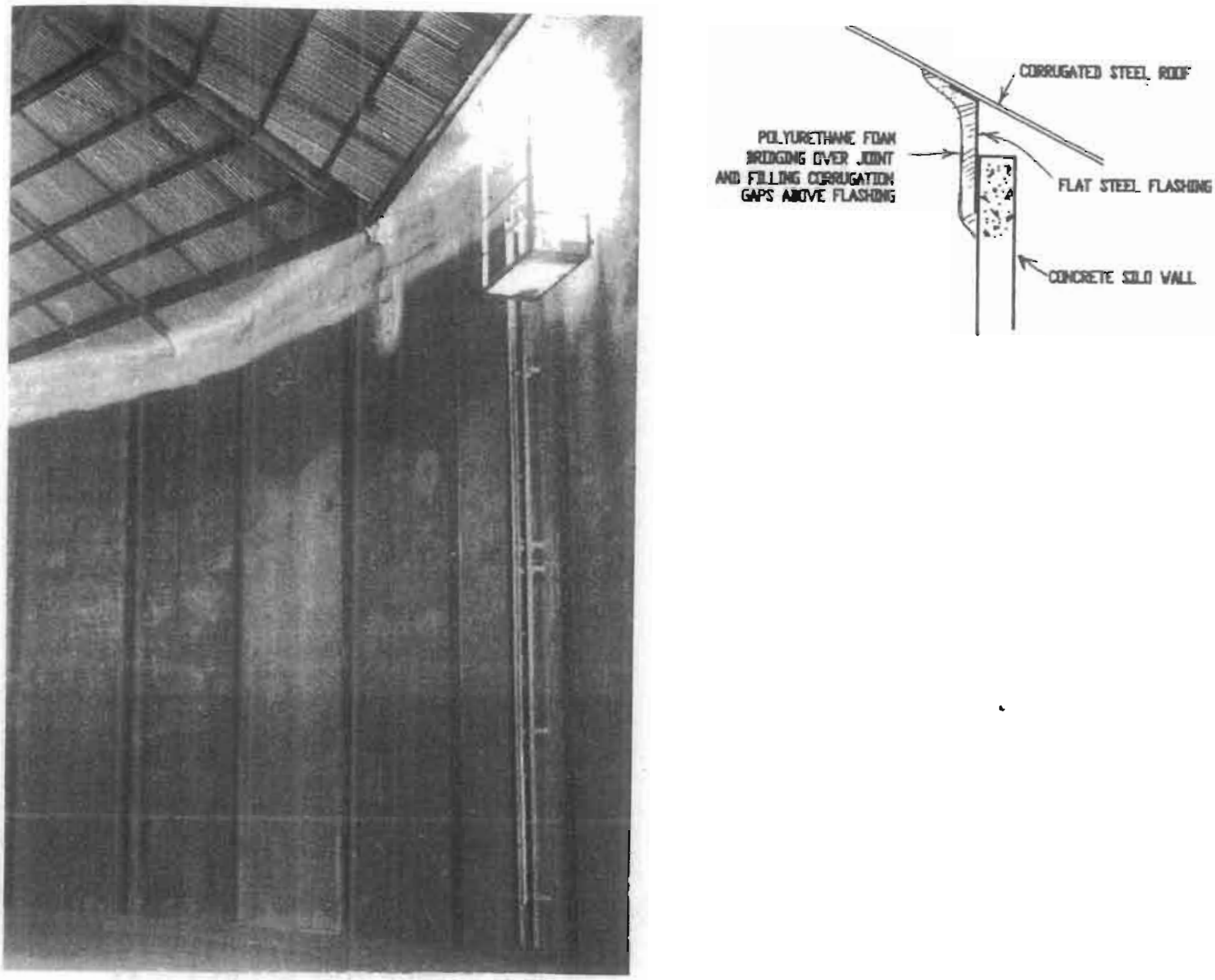


Fig. 10. This figure illustrates the application of polyurethane foam for sealing the joint between the concrete wall and corrugated steel roof of a squat silo.

rate to control internal pressures. They must be designed (or adjusted) to operate at positive and negative pressure differentials below the critical values which could cause structural damage (specifications for ventilators are discussed later in this paper).

White Painting

While pressure venting is essential for structural safety, it conflicts with gastightness requirements. It is thus important to take steps to minimise the amount of air movement into and out of the storage enclosure. White painting of the outer surfaces of steel clad structures has a dramatic effect in reducing temperature changes inside. In sunny conditions, the internal temperature of a white painted steel clad structure can be some 10°C lower than inside an unpainted galvanised steel structure, while the surface temperature of the steel may be 30°–40°C lower. Such a temperature reduction will significantly reduce the amount of air displaced through thermal expansion. Similarly, radiation losses during darkness will be reduced from a white painted structure, minimising air intake from contraction of the internal atmosphere.

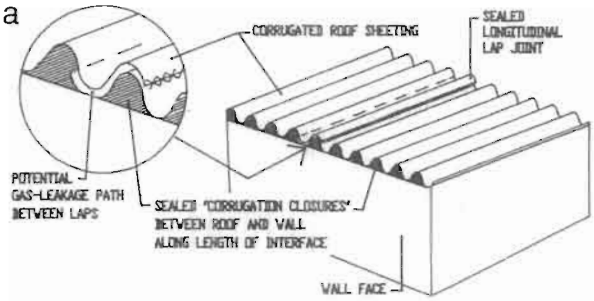
Because of the thickness of concrete sections used and their relatively low thermal conductivity, white painting of concrete structures is not normally necessary

Detail Design of Openings

It is important that the various openings fitted to grain storage structures be designed to facilitate sealing to specified levels of gastightness.

Openings for Personnel Access

For ease of access, manholes should be hinged openings with doors that are both rigid



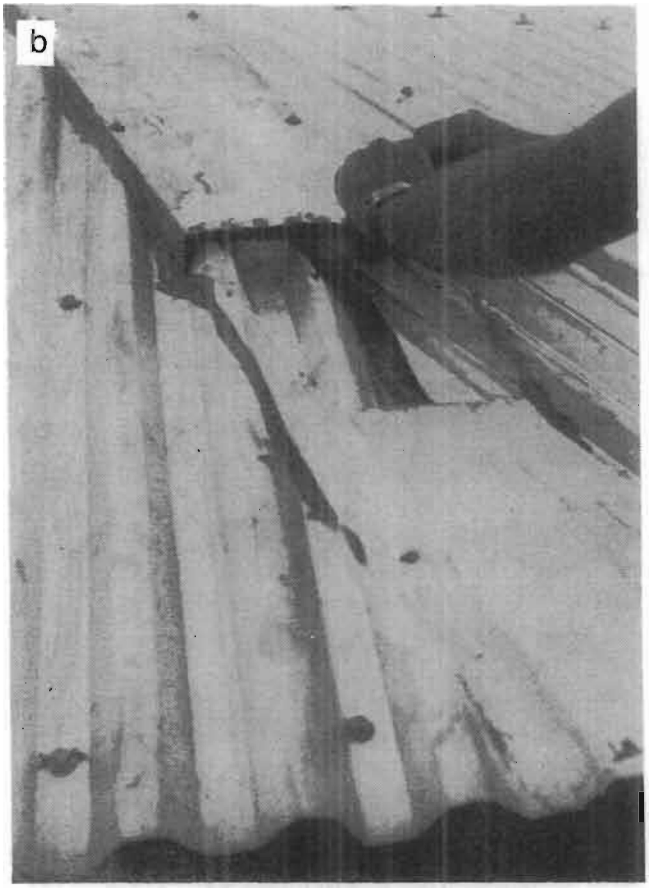


Fig. 11. (a) Location of a potential gas leakage path along sheeting laps. (b) Sealing under ridge capping. Note that sides of capping are sealed with silicone.

and light (Fig. 12). Rigidity is desirable since it minimises the number of fixings required to seal the closed door against a gasket.

Access doors that are not subject to grain pressure normally open outwards, while those that are should open inwards so that they cannot be opened accidently when the storage contains grain. The grain pressure will also assist in holding the door against the sealing gasket.

A combination of lightness and rigidity can usually be achieved by use of relatively light plate to form the door itself and stiffening its perimeter by attaching flanges or stiffeners.The gaskets used should be capable of sealing the door without further application of silicone type sealant. Appropriate gasket materials are discussed later, under specifications for gastight sealing.

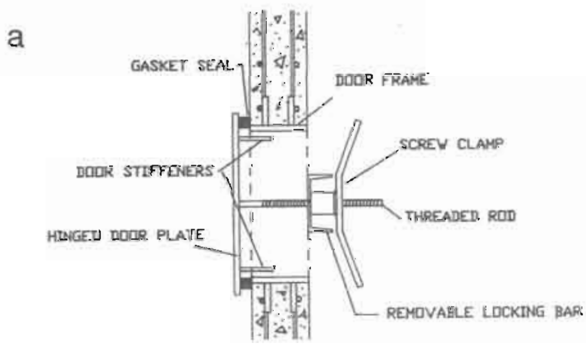
Machinery Access Doors

Access may be required for machinery or equipment, particularly into flat-bottom silos. Such openings are generally larger than those for personnel and may have to accommodate large machinery such as front-end loaders (Fig. 13). The doors normally open outwards since it is often necessary to drain residual grain from inside before gaining entry.

Sealing of machinery access doors can usually be achieved with an appropriate gasket. Clamping forces will need to be high if the door is subjected to grain pressures, multiple bolt fastenings around the perimeter usually being needed. Sealing effort can be reduced (as can the weight of the door) if grain pressure is carried by either an internal load bearing door or removable louvres.

Grain Inlet Chutes

It is normal practice for gas-sealing of inlets and discharge chutes to be carried out



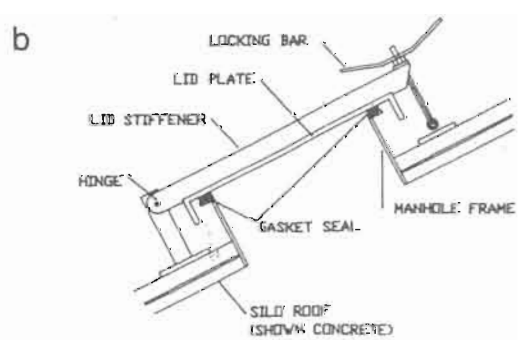


Fig. 12. (a) Typical inward-opening manhole subject to grain pressure when the silo is loaded. (b) Silo roof manhole with outward opening door.

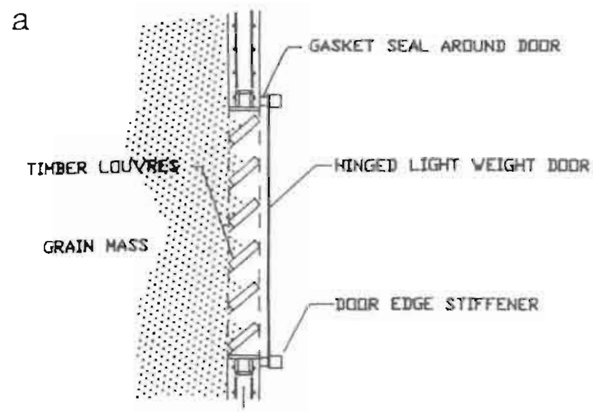


Fig. 13. Machinery access doors: (a) light door with internal louvres; (b) heavy door able to cope with grain pressures and wall stresses.

manually. Not only is it generally safer, in that the fumigator has to physically check valve settings and seals before fumigating, but it is also much less costly than automating.

Where a grain path is to be sealed, it is normal to use a retractable or removable plate, which can be withdrawn from the grain stream when the chute is in use. A commonly used sealing method provides a means of manually inserting a sealing plate (or diaphragm) into the chute and compressing it, either with bolts or clamps, to render it gastight. The system illustrated in Fig. 14 is extremely cheap and

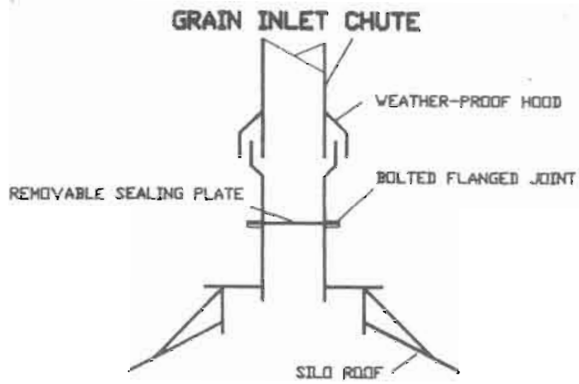


Fig. 14. Sealable silo inlet chute.

effective and offers an additional benefit (in some applications) of providing for relative movement between the chute and the storage structure.

Grain Discharge Openings

Gas sealing of gravity-fed discharge chutes usually entails use of slide gate to make the seal (Fig. 15). This can be done either by jacking the valve plate upwards until it seals against the discharge chute (the plate being lined with rubber to form a gasket), or by jacking a sealing ring down around the outer edge of the valve plate. The latter is probably simpler since jacking of the valve plate means that it has to be moved against the grain pressure.

An alternative arrangement is to enclose the valve in a gastight enclosure and to fit a separate sealing plate below it when required.

Another type of valve which has reportedly been used with success is a simple knife gate valve as used for controlling liquid flows. These are manufactured as proprietary items and come in a range of sizes, being commonly available up to 600 mm diameter. Manufactured with stainless steel components and internal seals, they require no secondary sealing mechanisms since the automatically seal when closed.

Non-gravity discharge by means of a conveying device may require either gas-sealing of the conveyor itself (Fig. 16(a)) or removal of the conveyor to allow sealing to be carried out (Fig. 16(b)).

Fans, Ventilators, and Associated Equipment

There is no contradiction in the concept of a gastight aerated storage. Aerated storages can

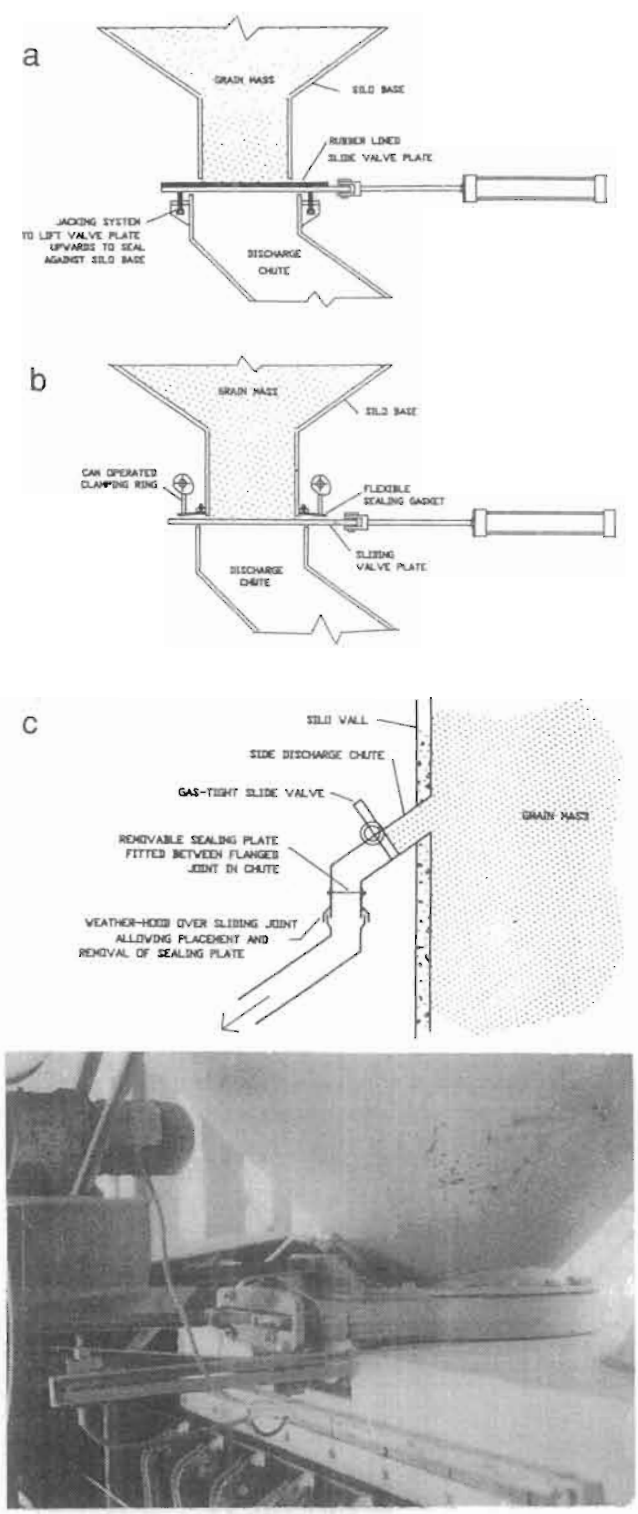


Fig. 15. (a) Gas sealing of discharge valves. (b) Downward clamping of sealing ring around valve plate. (c) Sealing plate in chute below valve. (d) Knife gate valve.

readily be made gastight, and gastight storages can also be aerated provided care is taken in the design of fans and air vents.

Axial fans (commonly used on horizontal sheds) normally incorporate direct-drive motors mounted within the air-stream. Such fans can be readily gas-sealed by fitting a sealing plate over the inlet opening (Fig. 17(a)). However, where phosphine fumigation is proposed it is advisable to remove the fan and seal the aeration inlet duct, so as to avoid damage to the motor windings.

Centrifugal fans (usually used for aerating vertical silos) should be fitted with a stuffing-box seal where the drive shaft passes through the outer casing (Fig. 17(b)). A removable blanking plate can be fitted to the fan inlet, which should be flanged to facilitate attachment of the plate.

Aeration ventilator openings should be specifically designed for ease of sealing with flanged ends for attachment of blanking plates (Fig. 17(c)).

Pressure Relief Valves

Oil bath and weighted diaphragm types of pressure relief valve are in common use. Both remain gastight below their release pressure.

An oil bath valve consists of a steel chamber partly filled with oil and divided by a partitioning plate, the bottom of which is immersed in the oil (Fig. 18). One side of the chamber is vented to atmosphere, the other to the storage. Air entering or leaving the storage must pass below the partition and through the oil; the pressure at which the passage of air will begin in either direction is controlled by the depth that the partition is immersed in oil: the

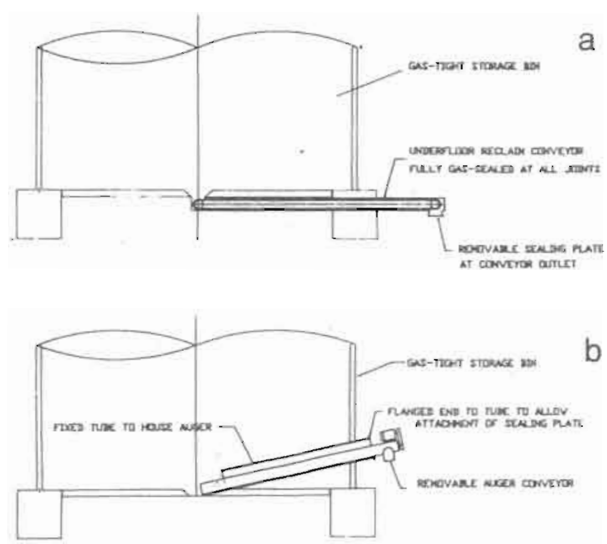


Fig. 16. Gas sealing of discharge conveyors: (a) sealing of the conveyor; (b) removable conveyor with sealable access tube.

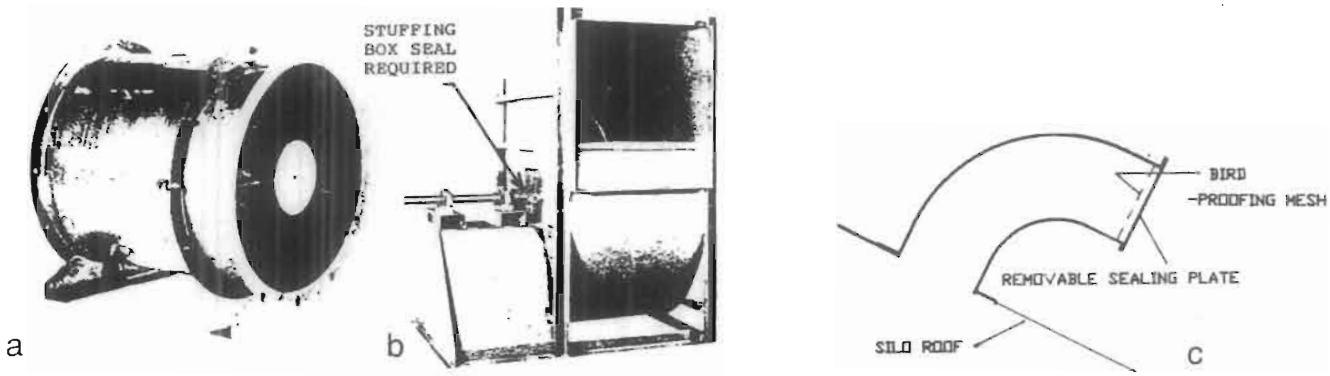


Fig. 17. Sealing fans and ventilators: (a) axial fan; (b) centrifugal fan; (c) ventilator.

deeper the oil, the greater the pressure differential that the valve will sustain. The wider the oil bath the greater the airflow rate which can be passed.

A diaphragm valve consists of a counterweighted sealed diaphragm which is lifted off its seating at a predetermined pressure differential that is adjustable by the mass of counterweight (Fig. 19). Proprietary valves are available with separate diaphragms for relieving positive and negative pressures. Such devices are relatively simple and could be fabricated to suit individual needs when proprietary valves are unavailable or unsuitable.

There appear to be no guidelines in common use for sizing pressure relief valves; however, it is suggested that a vent area of approximately 0.1 square millimetre for each cubic metre of storage volume should be sufficient to relieve pressure differentials resulting from internal air temperature changes of 1°C per hour (0.1 $mm^2/m^3/°C/hour$). A good design guide is 1 square millimetre of area per cubic metre of storage volume.

Electrical Fittings

It is important to seal or otherwise protect electrical equipment inside or communicating with any storage where phosphine fumigation is to be carried out. Phosphine reacts aggressively with copper and will quickly destroy electrical components which it comes into contact with.

Retro Sealing of Older Storages

The previous sections have discussed the design and construction of new storages in order to achieve gastightness.

Older storages were seldom built with gas-sealing in mind and hence they usually present much greater difficulties in sealing. While it may be technically possible to seal any type of storage, costs may become prohibitive in some instances.

Methods and materials used to seal older storages are similar to those used for sealing new ones. However, the amount of sealing effort is likely to be greater and structural modifications may be needed; for instance, modifications to doors and other openings to facilitate sealing, closing up of gaps and openings, strengthening structural members, and extra fixing of cladding. Once the structure is modified, the actual sealing work is generally carried out as for a new structure (Woodcock 1983).

A method of sealing large door openings commonly used in Western Australia involves special light-weight 'sandwich panel' sealing doors specially made up to fit the opening. The sandwich panels consist of polystyrene foam sheeting reinforced with a fibreglass skin. They have been found in some situations to be more economical than modifying the original door to render it gastight. The panels are clipped into place on the outside of the load-bearing door and the edges sealed using a bandage-type seal (see subsequent section on **Bandage Seals**).

A very important consideration when sealing old structures is to establish the positive and negative internal pressures which it is capable of safely supporting, and to provide pressure relief valves accordingly (Ripp 1985).

There have been a number of publications giving detailed descriptions of sealing work on individual storages.

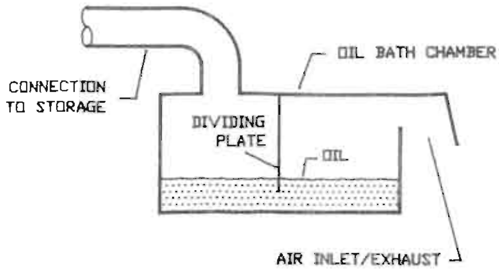


Fig. 18. Oil bath type pressure relief valve.

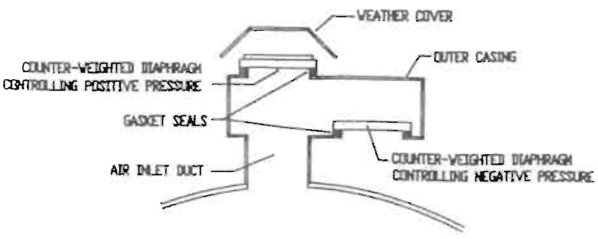


Fig. 19. Diaphragm type pressure relief valve.

Sealing Materials

Such a wide variety of sealing materials are available that a full coverage of them is beyond the scope of this paper. This paper will discuss those material types commonly used for storage sealing. It should not be assumed that other materials not covered in this paper are unsuited to the purpose.

Plastic (Non Elastic) Joint Sealants

Sealants in this category include bitumen and butyl type mastics. They can be useful as 'pre-formed' strips but have been largely superseded by other sealant types in recent years.

Such sealants can be useful in high compression joints where uneven surfaces are brought together. High compressive stress will force the sealant to flow into gaps and surface blemishes to form a seal. A typical application is where pre-cast concrete roof panels or a prefabricated steel roof is placed on top of a concrete silo wall (Fig. 20). The surface at the top of the wall will often be uneven and a plastic sealant will 'flow' into the voids under the weight of the roof. The sealant may, however, need to be retained with, for example, elastic foam strips, to prevent it flowing out of the joint.

Since the plastic sealant is resistant to rupture, seals of this type will tolerate a high degree of shearing movement. Plastic sealants are not, however, recommended for non-compressive joints since they cannot accommodate tensile stresses. Also, they often have a tendency to become brittle, particularly when exposed to sunlight.

Elastic Adhesive Joint Sealants

Polysulphide and silicone type sealants fall under this heading. They are particularly useful for sealing non-compression joints and, since they are applied after the joint is formed, for 'retro-sealing' compression joints. Such sealants are usually applied by caulking gun and need to 'cure' for a period of time to develop their elastic properties. They need to develop a good adhesive bond to the surfaces to which they are applied so that they will maintain intimate contact with them if tensile or shear stresses occur.

Silicone and polysulphide sealants are used principally for sealing abutting surfaces (concrete to concrete, steel to steel, or steel to concrete) and will tolerate some tensile and shearing stresses before rupturing. The sealant cross-section needs to be carefully controlled to maximise the amount of deformation it will tolerate, general principles being that the depth of sealant should be about half its width and that a bond-breaking strip be incorporated under the seal to ensure that it is bonded only at its sides (Figs 21 and 22).

Modern silicone sealants are generally more easily applied than polysulphides. Silicone sealant is a 'one-part' pre-packaged material

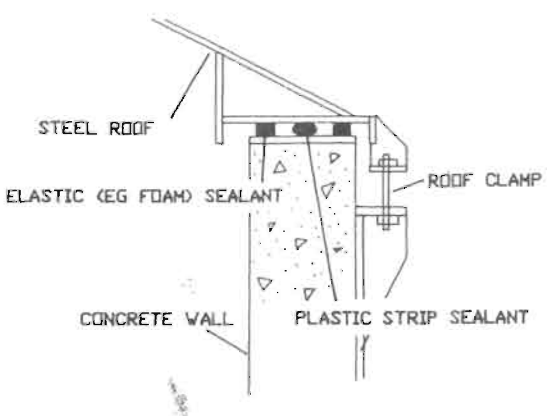


Fig. 20. Typical use of plastic sealant in a compressive joint between a silo roof and wall.

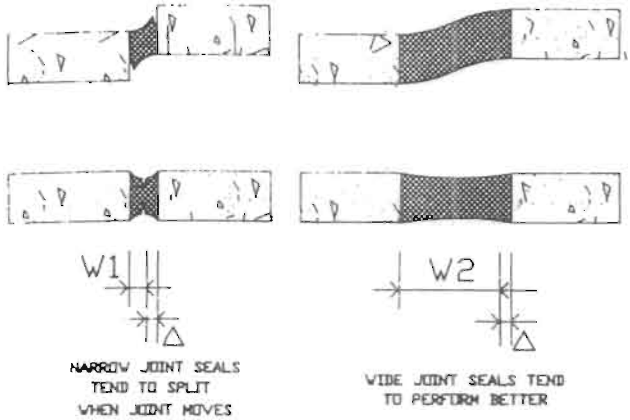


Fig. 21. Sealants perform better if they are applied so that the seal formed is wider than its depth.

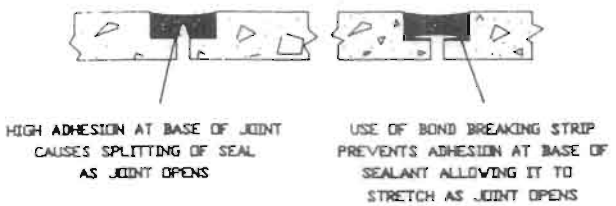


Fig. 22. Sealants perform better if not bonded underneath.

usually applied from a cartridge inside a caulking gun. Curing is by chemical reaction with atmospheric moisture.

Polysulphides are supplied in two parts which have to be thoroughly mixed together on site immediately before application. Curing is by chemical reaction between the two components. Sealant failures resulting from inadequate mixing are not uncommon.

While both silicones and polysulphides types have very good bonding properties, very careful surface preparation and priming is usually necessary for good bonding to be achieved, particularly in the case of polysulphides. The latter may also deteriorate and become brittle when exposed to the sun for extended periods, a defect not generally shared by the silicones.

Silicones are available only in 'caulking' grade—i.e. they must be 'gun applied'—whereas 'pourable' grade polysulphides are available for filling horizontal joints. Nevertheless, polysulphides have been largely superseded by silicones in recent years. Generally, silicones are much easier to work with (requiring no mixing) and cure more quickly and reliably. Silicone sealant specifications receive further mention in the next section.

Acrylic-Based Sealant Paints

Of all the various forms of sealants used in gas-sealing of storages, acrylic-based sealant paints are by far the most important. They can be used on virtually any substrate and adapted to seal most types of joints, cracks, or other potential routes of gas-leakage. In fact, it should be possible to seal most storages using only this type of sealant.

Sealant paints are generally acrylic-based emulsions with a high solids content. They are easy to apply, bond well to most surfaces, bridge over small cracks, dry and cure quickly, retain flexibility and elasticity in the event of subsequent joint movement, and are easy to recoat.

Acrylic sealant 'coatings' generally contain at least 50% solids, either as pure acrylics (plus pigments) or mixtures of acrylics and other plastics such as styrenes (referred to as copolymers). Higher solids content coatings yield thicker films, while the addition of thixotropes can produce mastic-type sealants suitable for caulking wide gaps.

Acrylic and copolymer sealant coatings can be used in a wide range of sealing applications including:

- sealing porous surfaces (e.g. concrete, masonry, timber, fabric);
- sealing cracks in concrete;
- sealing lap joints in steel cladding; and
- as bandage seals.

Acrylic sealant coatings are easy to apply and are relatively forgiving of poor application procedures. Good adhesion can be achieved on most surfaces without the use of primers. Nevertheless, as with all paints, surface preparation is critical to good performance, removal of oils, dirt, and loose particles being essential before application of the sealant.

Since they are relatively inert and unaffected by ultraviolet light, acrylics can be expected to give excellent durability in external applications. They are also flexible and extensible, although some loss of flexibility is likely to occur due to changes in temperature (Lloyd 1985). Finally, they are non-toxic and therefore can be used in contact with foodstuffs. A later section of this paper—**Materials Specifications for Sealants**—provides further information on acrylic sealant membrane application.

Polyurethane Sealant Membranes

Flexible polyurethane is another material with potential for storage sealing, although it is much more expensive than acrylic compounds and may include toxic components that render it unsuitable for applications which place it in contact with foodstuffs.

Flexible polyurethanes do, however, offer excellent adhesion and flexibility in external applications, and may outperform acrylics in terms of bond strength and elongation. This type of membrane sealant may therefore find a use in critical sealing situations where its good adhesion and excellent strength and elongation warrant the high cost.

Bandage Seals

'Bandages' are used for bridging gaps too wide for a sealant coating. They are especially useful for sealing joints where a great deal of movement can occur (Fig. 23). The edges of the joint are coated with sealant (e.g. acrylic) and a cloth or fabric 'bandage' is then placed across the joint while the sealant coating is still wet. The bandage is then painted over with sealant to make it gastight. Since the fabric acts mainly as a support (or bridge) for the sealant coating, its composition is, to some extent, not critical. However, a coarsely woven material is preferable to ensure good penetration and adhesion of the paint. Strength can also be advantageous in some situations where there is a risk of mechanical damage. In such cases, glass-fibre or polyester fabrics are commonly used. Where joint movement is expected, it should be accommodated by placing a concertina-type fold in the part of the bandage over the joint.

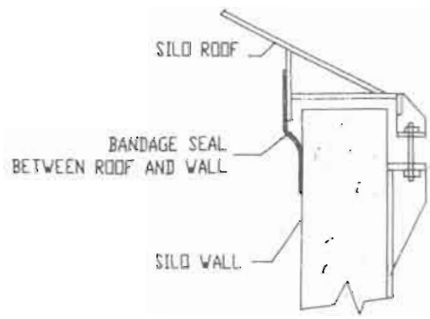
Acrylic sealant coatings are usually employed to coat bandage seals of this type, but an alternative is to use a preformed PVC membrane bonded to each side of the joint with an epoxy type adhesive. Such a seal will give excellent and reliable results but is relatively difficult to apply, often requiring specialist applicators.

Sprayed Rigid Polyurethane Foam

Where very large apertures require sealing, it is usual to close them with some form of bridging before sealing. Timber, galvanised iron, and mortar are often used for this purpose, as are bandages as described above.

Polyurethane foam is a very useful material for bridging gaps, particularly where access is difficult or where the joint is irregular and difficult to close. The material is formed from two liquid components which, when mixed together, expand to 20–30 times their original volume by the rapid development of the cellular foam structure. The foam then hardens to become a relatively strong and rigid structure. It also bonds extremely well to most surfaces provided they are properly cleaned and dried. Porous surfaces may need priming or pre-sealing (Anon. 1987).

Application is usually by spray (the two components being mixed together in the spray nozzle), but it is not uncommon for the liquid mixture (suitably retarded) to be poured into joints or cavities where access is difficult. These then become filled as the foam expands.



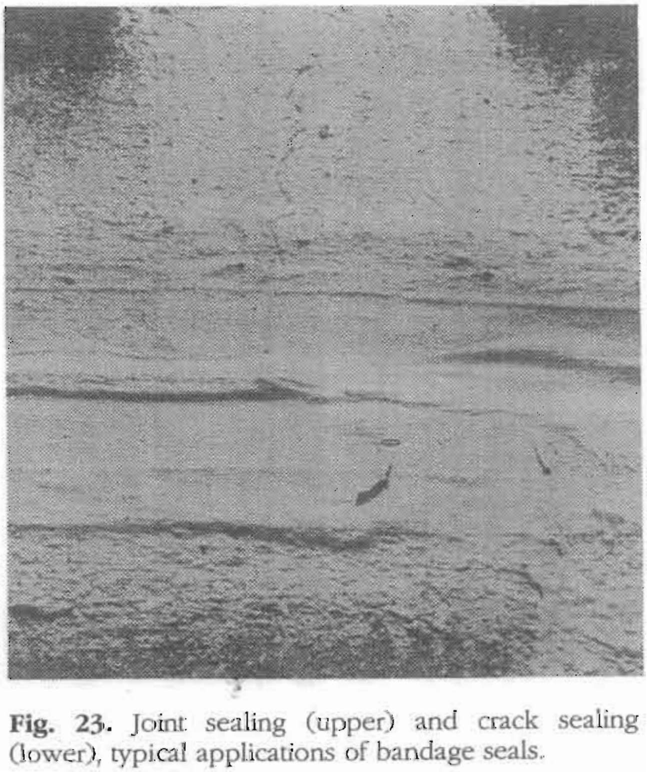


Fig. 23. Joint sealing (upper) and crack sealing (lower), typical applications of bandage seals.

Polyurethane foam is widely used as a heat insulation material; for instance on steel roofs. It can also be used to seal and strengthen badly corroded roofs. Its principal role in grain storage sealing is however, not as insulation, but as a 'bridging' medium. Further information on its use is given under **Specifications for Gastight Sealing.**

Gasket Materials

Gasket seals are required to perform so great a range of functions that it is not possible to describe all suitable materials. Generally, they need to combine good elasticity with sufficient rigidity to accommodate unevenness in the surfaces being joined. Gasket material specifications are discussed briefly under **Specifications for Gastight Sealing.**

Specifications for Gastight Sealing

Whether gas-sealing is to be undertaken by a contractor or on-site labour, and whether it is to be carried out on a new or old structure, the level of gastightness to be achieved needs to be specified. This section looks primarily at the specifications applicable to gas-sealing work by contract. Material specifications are also discussed.

Specification for Sealing Contracts

In drawing up a sealing contract the first choice to be made is whether to seek a performance specification or to specify the precise sealing methods to be adopted. Current practice in Australia is almost universally to use performance specifications, since the onus is then clearly placed on the contractor to achieve the required degree of gastightness. Such a specification normally states the criteria for acceptance of the degree of seal achieved (usually by means of a 'pressure-decay test') and the contractor is allowed to undertake the work in any way he chooses. The onus is thus transferred almost wholly to the contractor to achieve the desired result and the 'risk' is carried by him.

The alternative—specification of materials and sealing methods to be used—leaves a high level of uncertainty as to which party carries the risk. If the specified seal is not achieved, it may be either the contractor's responsibility because of poor workmanship or the client's as a result of inappropriate specification. Uncertainty and dispute is then almost inevitable in the event of failure to meet the specified performance.

A performance specification does not, however, assign all risks to the contractor. Some risks will always remain with the client, including the following:

- The contractor may fail to achieve the specified standard and back down on the contract. This is best avoided by engaging a reputable contractor with proven competence.
- The contractor may use poor quality materials or poor sealing methods. While these may achieve the specified test standards, they may also have poor durability and subsequently fail in service.
- The storage enclosure may have defects affecting its ability to be sealed. If the storage sealing is part of a 'design and construct' contract package, the responsibility will be with the contractor to overcome such difficulties. If the sealing contractor is not responsible for structural adequacy of the enclosure, then contractual complications will arise if structural problems (e.g. excessive deflections under test pressure differentials) make sealing difficult.

Contractual difficulties are best avoided by unequivocal definition in the contract documents of where responsibilities for risk are to lie. Clients should recognise that they should not expect to get something for nothing, and that they should expect to pay for what they get. Quality seldom comes cheap and the lowest price is not necessarily the best. If the client wants the contractor to carry risk, then this should be reflected in the contractor's price. If not, then the client must be prepared to pay for problems beyond the control of the contractor. Documentation should be drafted so as to anticipate, where possible, the problems that may arise, and to define cost responsibility as clearly as possible for every situation.

In essence, the most appropriate specification for most storage sealing contracts should incorporate a performance-based objective for the contractor, where the degree of seal that must be achieved is clearly defined, as are the acceptance criteria.

A performance-based specification automatically precludes the use of a method based specification. A client cannot tell a contractor precisely how to do the work and then hold the contractor responsible for the outcome. A performance-based specification thus removes some of the client's opportunity to control the quality of the work as it is progressed.

There are various means of overcoming this problem:

- Quality standards for materials that can be used on the job (allowing the contractor to select conforming materials of his choice) can be specified.
- Alternatively, the contractor may be required to submit for approval, at the tender stage, full details of all materials he proposes to use.
- In addition, the contractor should be required to submit for approval at the tender stage full details of the sealing methods and procedures that he proposes to use.

In this way, the contractor chooses his own materials and methods and thus retains full responsibility for performance. At the same time he makes a commitment at the time of tendering as to the materials, procedures, and methods which he intends to adopt, thus giving the client the opportunity to assess the quality of the proposal before awarding the contract, and to monitor (and to some extent control) the quality of the work as it is undertaken.

A warranty period should also be clearly defined, spelling out the guarantees as to performance that are to be provided by the contractor. Often a 5-year warranty is specified which requires an annual gastightness test by the contractor and repair of any leaks that are found.

A properly drafted (and preferably a standardised) set of General Conditions of Contract should be used, clearly defining how the contract is to be administered and where contractual responsibilities lie. Standard Conditions of Contract are often available from national 'Standards' organisations and government departments [e.g. Australian Standard AS 2124 (Anon. 1986) or the (Australian) National Public Works Committee's (NPWC) Conditions of Contract].

Finally, it should be emphasised most strongly that the choice of contractor is of paramount importance in achieving successful results. It is strongly recommended that the past performance of a prospective contractor be thoroughly investigated, and client references carefully followed up.

Material Specifications for Sealants

As discussed earlier, minimum quality standards should be specified for sealing materials and methods of application. The following sections look at specifications for some of the commonly used sealants.

Acrylic Sealant Coatings

As noted previously, acrylic sealant coatings are by far the most widely used materials for grain storage sealing. It is thus important that the most appropriate materials be selected for the purpose.

Desirable properties of sealants to be applied externally include:

- non toxicity
- ease of application in a single coat.
- durability
- gap-bridging ability
- good adhesion to a variety of surfaces
- relative impermeability
- flexibility over a wide temperature range
- extensibility over a wide temperature range
- high tensile strength
- low shrinkage

For internal application, the following additional properties are important:

- abrasion resistance if in contact with moving grain
- surface hardness
- suitability for contact with foodstuffs
- non-reactivity with fumigants such as methyl bromide, phosphine and CO_2

In Australia, at least, there are no clearly definable test standards for sealants and there does appear to be a clear need for the formulation of more precise testing procedures, and performance criteria based on these tests, to allow comparative testing of sealant coating materials to be systematically undertaken. It is beyond the scope of this paper to discuss in detail what might be appropriate test methods and performance criteria. However, the following brief comments are included to highlight the needs and problems.

Toxicity. In Australia, most commonly used paint coatings have a 'GPC' approval issued by the Government Paint Committee. Such approvals imply that a Material Safety Data Sheet (MSDS) for the paint product has been checked for currently known harmful chemicals as listed by the U.S. Food and Drug Administration (FDA) and other regulatory and testing agencies. Thus, in general, approved paints do not contain toxic compounds and all acrylic coatings with GPC approvals can be assumed to contain no known harmful chemicals.

When specifying coatings, it is strongly recommended that a Material Safety Data Sheet or similar information be checked for any sealant which is to come into contact with grain.

Durability. It is inappropriate to specify a level of durability since it is always difficult to determine and must ultimately be assessed by field performance. Accelerated UV testing could provide an indication of UV susceptibility. The Western Australian grain handling authority's test procedure, for example, involves 2000 hours exposure to mercury discharge. Condensation testing (AS1580 452.1) (Anon. 1981a) and salt spray testing (AS1580 452.2) (Anon. 1981b) could give comparative indications of susceptibility to moisture etc. It should be noted that most acrylic type sealant coatings have no corrosion inhibitors and seldom offer good corrosion protection on their own (without primer).

Gap-bridging Ability. This is an important property from an applicator's point of view and one which can affect the cost of applying sealant coatings. An implied requirement of the existing 'standards' in Australia is that coatings should be able to bridge 1.5 mm gaps. Since most coatings will meet this requirement a need exists for 'comparative' testing of coatings. While no standard test is currently in use, it may be possible to assess performance in this respect by coating a sheet of etched galvanised steel punched with holes of varying diameters. Bridging ability could be measured by the maximum diameter hole which will be covered over by a film of specified thickness.

Elongation or Strain. Strain is defined as the ratio between the change in length and the original length, i.e.

$$\text{Strain} = \frac{\text{Stretched Length} - \text{Unstretched Length}}{\text{Unstretched Length}}$$

This is a very important property for an elastic sealant. Values of 300, 500, and even 700% are often quoted by manufacturers, but it should be recognised that such figures are obtained using narrow test strips that are free to contract laterally as they are stretched. Were this contraction to be inhibited, the ultimate strain figures would reduce significantly.

When applied to a sealed joint, the coating is usually equivalent to a very wide and short test sample that is incapable of significant change in width as a result of elongation. It is suggested that a standardised test should reflect this fact, utilising perhaps a 50 mm wide test sample clamped 5 mm apart. The results should give a more factual interpretation of the ability of a material to accommodate joint movements.

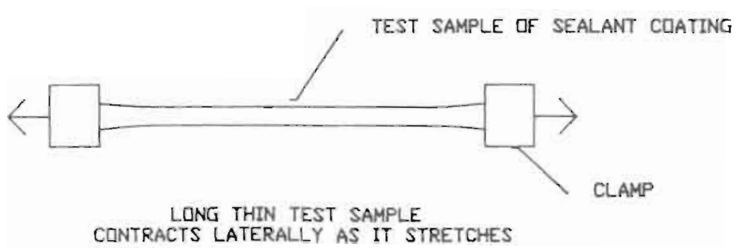
Tensile Strength and Adhesion. The test suggested above to measure elongation should also yield a realistic figure for tensile strength (Fig. 24). Strength, however, is not in itself a particularly important property and is relevant only in relation to adhesion or bond-strength.

The relationship is important in situations where unexpected movement occurs as, for instance, where a new crack occurs in a concrete surface underneath a sealant coating. If the coating bond is very high, such that adhesion is maintained almost to the edges of the new crack, then the unstretched length is close to the initial crack width which is zero. Thus the strain tends towards 'infinity' and tensile failure is inevitable (Fig. 25).

Where adhesion is weaker in relation to tensile strength, progressive bond failure will occur at the edges of the crack thus increasing the effective unstretched length. Strain in the coating is thus reduced and tensile failure less likely to occur.

Coating adhesion is highly dependent on the nature of the surface being coated. It is also of particular relevance to coating performance when applied to brittle substrates such as concrete, which itself is a highly variable material not least in terms of its surface qualities. It is thus hard to envisage a standardised test which will reliably indicate the performance of a coating in all circumstances.

Nevertheless, it is suggested that a simple test providing good comparative indications of



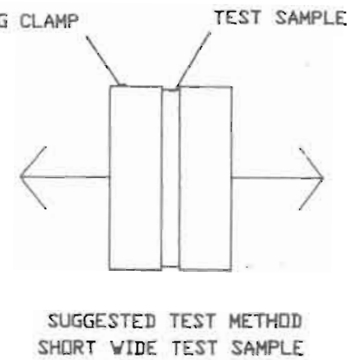


Fig. 24. Methods of testing tensile strength of sealant coatings.

performance could be devised by using a 50 mm wide strip of standard grade glass paper to represent a standard surface texture (Fig. 26). This could be precut before being coated with a nominated thickness of the sealant coating. Tensile testing of the cured sample would provide a relationship between stress and strain and, in particular, should give guidance as to loss of adhesion that takes place prior to failure. It should indicate the coating's potential performance when used for sealing concrete surfaces subject to cracking and movement. The current criterion for this property set by CSIRO in Australia stipulates that a '100% extension of a 0.3 mm wide crack should be withstood without failure'.

Abrasion Resistance and Adhesion. While good adhesion is potentially a negative attribute in the circumstances just dealt with, it is, on the other hand, essential in the context of ensuring that the coating will not fall off or becoming detached as a result, for example, of air pressure differentials across it. In abrasive situations, such as the internal surfaces of bins, good adhesion becomes of even greater importance.

Some acrylic based sealants are specifically formulated to improve abrasion resistance, but there appear to be no established test procedures to assess performance. There are, however, a number of procedures which could be developed into a standard test method; for instance, the loss of coating (by weight) from a disc of prepared substrate (e.g. graded sandpaper or etched galvanised steel) could be measured after it has rotated a certain number of times in contact with grain. Alternatively, a 'tumbler' type of apparatus could be used to compare abrasion resistance.

No quantitative standards have yet been set.

Surface Friction. Surface friction is an important property in circumstances where the internal wall surface of a silo is to be coated, as may be the case when interconnected concrete silos are to be sealed. The forces exerted by the grain mass on the walls of a silo are directly related to the wall surface roughness and, in general, reducing the friction between the grain and the wall will result in higher horizontal grain pressures and higher wall tension stresses.

If a coating is to be applied to the internal walls of a silo, it is important to know what effects it will have on grain pressures (Banks 1984). The Western Australian grain handling authority assesses this coating property using a standard 'pencil hardness' test (AS 1580–405.1) (Anon. 1978). It is questionable, however, whether such a test is reliable in determining

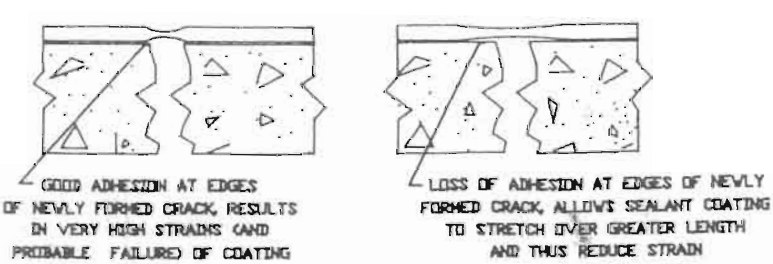


Fig. 25. Diagrams showing how sealant coatings bridge cracks better if their adhesion fails.

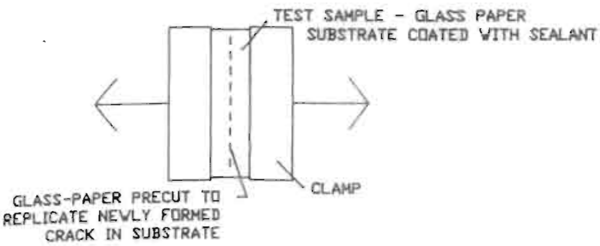


Fig. 26. Suggested method for testing tensile strength/adhesion of surface coatings.

the effects of a coating on the friction angle between grain and a silo wall and it is strongly recommended that an accurate determination of the kinematic angle of friction between grain and the coating surface be undertaken before a coating is selected.

Flexibility. The Western Australian grain handling authority specifies a bend test (as per AS 1580-402.1) (Anon. 1981c) requiring checking for cracking or detachment of the coating as applied to galvanised steel, when bent over a 6 mm diameter mandrel at 25°C. No evidence of cracking in the coating is permitted.

Permeability. The Western Australian grain handling authority's test standards specify permeability testing in accordance with American Society for Testing of Materials' E96 Procedure B. The acceptance criteria are not defined.

While it appears to be the case that specifications and acceptance criteria need to be better defined for sealant coatings, it should be recognised that a number of coating types have been successfully used for sealing a variety of storages. The Western Australian grain handling authority has had more experience with these coatings than any other grain industry group, and has conducted its own comparative testing of numerous products. It has also developed an extensive weathering and exposure testing site on the roof of one of its large horizontal grain storages, where several coating suppliers have applied their coatings side-by-side with those of their competitors.

Specifications for Gaskets

A gasket material needs to be:

- rigid enough to withstand the compressive forces applied to it;
- elastic enough to deform and conform to any unevenness in the surfaces being joined;
- resilient, i.e. reverts to its original shape when released from a deforming force;
- durable and chemically resistant; and
- gastight under moderate compressive stress.

Solid materials (e.g. rubber) will usually best suit situations where contact pressures are high. Rubber hardness should be specified by Shore-A or 'Duro' hardness, 40 or less indicating a soft rubber suited to forming gaskets.

Where contact pressures are low, cellular or foam gaskets are more appropriate. A number of types are available, including rubber, polyurethane, PVC, and polyethylene. Unlike polyurethane flexible foams, which are usually open-cell, polyethylene and PVC foams have the advantage of being quite inert and having a closed-cell structure, making them inherently gastight and non-absorbent. They are also available in a wide range of hardness. PVC foams are generally softer and more resilient than polyethylenes and may offer better sealing performance on lighter weight doors and closures.

Trial and error may sometimes be the best approach to selecting the most suitable material for a particular application.

Silicone Sealant Specifications

The term 'silicone sealant' defines a range of products that are very widely used throughout the building industry. It is surprising therefore that there are few industry 'standards' against which material qualities can be assessed.

It is important to recognise that there are different type of silicone sealants. Some, for example, bond better to steel and others to concrete, and some have better elongation properties than others and are more suited to sealing joints that accommodate movement. Importantly, some silicones release acids as they cure rendering them unsuited for use in contact with steel or concrete; 'neutral-cure' sealants should be specified for such purposes.

In view of the absence of general industry standards for silicone sealants, and the relatively small usage of the material in the grain industry, it is common practice to specify a suitable product from a recognised manufacturer and to permit the use of 'approved equivalents'.

Good quality spray polyurethane foam is not easy to produce and specifications should call for the engagement of an experienced applicator using high quality materials and good application equipment.

The most easily specified and verified measure of quality is the foam density, which should not be less than 32 kg/m^3 for non traffic areas, and 48 kg/m^3 where extra rigidity is required.

The specification should require that density be routinely checked during the spraying operation to ensure that quality is being maintained. Samples are cut from the workface with a sharp knife or sprayed onto a separate test panel, and visually inspected before density testing. A sample should be taken for at least every 200 square metres of coating. Coating thickness should also be checked regularly using a needle probe.

The formation of the foam is dependent upon the expansion of a refrigerant 'blowing agent', the rate of expansion being dependent upon the heat of the chemical reaction which forms the polyurethane material. Ambient humidity and temperature, and surface temperatures, are important factors which can affect the quality of the finished product. Special chemical formulations should be specified for high and low ambient temperatures.

Polyurethane foams are not weatherproof, and they are subject to U/V degradation. When applied externally, it is essential to overcoat them with an appropriate material to provide protection. An acrylic sealant coating (as previously described) is commonly used.

Gastightness Testing

General

In defining a performance specification for gas-sealing work, the test procedure and acceptance criteria must be clearly specified. Appropriate procedures and acceptance criteria have long been established by the CSIRO in Australia and have gained widespread industry acceptance (Banks and Annis 1980).

The test involves applying a pressure differential between the inside and outside of the storage enclosure by the development of a positive or negative internal pressure, and then measuring the 'half-life decay', i.e. the time taken for the pressure differential to reduce to half its starting value.

The acceptance criterion is for a half-life decay of not less than 8 minutes for a full structure or 15 minutes for an empty structure. The decay time for partially filled structures can be estimated on a pro-rata basis.

Because pressure differentials are affected by external factors such as temperature changes, wind, and barometric pressure changes, it is important that accurate testing be carried out under stable atmospheric conditions—ideally shortly before sunrise. This applies particularly to steel structures, which are subject to rapid temperature change from insolation.

Test Equipment

Equipment needed for pressure testing includes the following:

- A blower or suction unit to generate a pressure differential. For structures up to around 3000 m^3 capacity, a small hand-held blower, or vacuum cleaner, will normally suffice. For very large structures (or very leaky ones) a small axial fan is usually necessary to generate a pressure differential sufficient to conduct a test.
- A quick acting valve to isolate the storage from the air supply or, where an axial fan is used, it is usual to flange-mount the fan to the structure and to clamp a sealing plate over the outside of the fan when the specified starting pressure is reached.
- A manometer attached to the structure to measure the internal air pressure. For low pressure differentials, such as may be applied to a horizontal shed structure (say, less than 250 pa), an 'inclined' manometer is desirable for accurate measurements. For higher pressures, such as may be applied to a silo structure, a simple U-tube manometer is normally sufficient.

Test Procedure

The test procedure is simple.

1. Atmospheric conditions are checked for stability—usually intuitively for routine tests, but by measurement for experimental or other critical tests.

2. The blower device is connected to the structure by suitable means (e.g. flexible hose) and then switched on.
3. The pressure differential is monitored and once it reaches a value slightly in excess of the nominated test pressure, the cut-off valve is closed and the blower switched off.
4. A timer is started when the pressure differential drops to the nominated test pressure and stopped when the pressure reaches half this value. The decay time is recorded.

Detecting Gas Leaks

In preparing a specification for pressure testing of a storage some points to be followed are:

- Specify who is responsible for conducting the tests. Usually the sealing contractor will undertake the initial tests on the empty storage but the client may elect to conduct the tests when the storage is full and at the end of the warranty period specified in the sealing contract.
- Specify that all detectable leaks are to be sealed, even when the pressure standard is achieved.
- Specify methods of leak detection. To some extent, leak detection methods are chosen to suit the storage and the type of fumigant that will be used.

For independent, above-ground storages with no interconnecting galleries, it should suffice to use leak detection methods based on sound and a 'soapy water' test. In the latter, a mixture of detergent and water is sprayed over the storage surface, and leaks are revealed by bubbling.

In some cases (e.g. when testing for leaks through the floor of the enclosure, or listening for leaks in the roof) it is often more appropriate to apply negative pressure and to search for leaks on the inside the structure.

Leaks often become evident by inspection from inside the structure when application of a positive pressure opens gaps through which daylight can be seen.

When a storage structure interconnects with conveyor galleries or adjacent enclosed workspaces, the existence of leaks should be much more closely investigated even after the pressure decay test is successful: a serious hazard would be created if any gas leakage paths vented into such areas.It is thus essential in such circumstances to employ appropriate gas monitoring equipment to thoroughly test for the presence of gas during the first fumigation of the storage.

Conclusion

Fumigation is one of the most important weapons available in the ongoing war against insects causing grain losses. At the same time, ineffective fumigation practice represents a long-term threat to the usefulness of available fumigants because of the risk of insect resistance developing. The key to effective fumigation practice is the availability of an adequately sealed storage.

There can be few circumstances where the cost of sealing new storages to an adequate standard of gastightness cannot be justified, and there are few circumstances where adequate gastightness cannot be achieved if appropriate design detailing has been adopted. The technology is simple and straightforward and requires little more than common sense and careful attention to detail to ensure that satisfactory results are achieved.

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