Design and operation guidelines for municipal sized surface water limestone contactors

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Abstract

Treatment technologies and know-how to address soft water problems of aggression and corrosion via conventional stabilisation using lime and carbon dioxide are readily available for larger water supply systems and areas close to technical support centres. However, treatment technologies and know-how for small-scale and/or remote rural application are not as readily available. Accordingly, CSIR conducted research into the use of limestone for stabilisation purposes, which culminated in the development and implementation of small and medium scale (municipal size) limestone contactors.

To date, approximately 14 municipal size limestone contactor systems have been installed in South Africa with treatment capacity ranging from 2 Ml/d to 18 Ml/d, with a 50 Ml/d limestone contactor system currently under construction in the Free State province. However, the medium-term performance efficiency of these units in negating soft water problems has not been thoroughly documented. Furthermore, nearly all of the operational municipal systems in South Africa have been designed by CSIR, using process design and operating guidelines developed by CSIR. Accordingly, Water Research Commission funded studies for the documentation of both limestone contactor performance, and transfer of process design and operating guidelines into the broader water treatment community.

This paper will review the performance of operational municipal limestone contactors in South Africa, and present CSIR limestone contactor process design and operating guidelines.

Introduction

Where snow melt and mountain catchment waters are found, and where the underlying geology is lacking calcitic and dolomitic deposits, calcium and carbonate deficient waters with low pH occur. Typically these waters have low conductivity (5 to 50 mS/m), low total alkalinity (0 to 20 mg/l as $CaCO_3$), low calcium (0 to 20 mg/l as $CaCO_3$) and low pH (4.0 to 7.0). Approximately 40% of the surface waters of South Africa, and all the surface waters of Lesotho, characteristically have low calcium, alkalinity and carbonate species concentration. In addition, virtually all of the groundwaters of the southern and eastern fringes of South Africa (up to approximately 200 km inland) have similar characteristics. Furthermore, conventional water purification, using floc agents such as ferric chloride, ferric sulphate and aluminium sulphate further depresses pH and total alkalinity prior to release of the purified water into the distribution network. These characteristics result in the water being aggressive (to cement concrete) and corrosive (to metals), attacking pipes, conduits and reservoirs.

For the many large and smaller towns utilising soft, acidic waters for domestic supply, aggressive and corrosive attack can have significant financial consequences (reservoir/pipe rehabilitation and lost water as a result of pipe bursts and leaks), whilst raised levels of metal corrosion by-products will also lead to a decrease in water quality.

Treatment technologies and know-how to address these water quality problems are readily available for larger water supply systems and areas close to technical support centres. However, treatment technologies and know-how for small-scale and/or remote rural application are not as readily available.

Accordingly, research, development and implementation was initiated by CSIR in developing the use of limestone for treatment of soft, acidic waters including (Mackintosh et al., 1998a):

- Identification and assessment of various limestone deposits.
- Research and development of city-sized "sidestream" stabilisation process.
- Research and development of a simplified (ie reduced technical barriers to implementation) city-sized "sidestream" stabilisation process.
- Ensuring commercial supply of water treatment grade limestone pebbles.
- Kinetic modelling of limestone dissolution.
- RDI of small user systems; both groundwater and surface water.
- RDI of fluidised bed-based processes.
- RDI of municipal sized fixed bed process.
- Mobile test rig for on- site experimental determination of reactor sizing and process design requirements for full-scale municipal implementation.
- Development of process design guidelines for municipal sized surface water fixed bed process.
- Overseeing the design and installation of full-scale municipal surface water limestone based stabilisation systems.
- Research and development of city-sized "sidestream" stabilisation process.

This paper provides a summary of design and operation guidelines for surface water fixed-bed limestone contactors. NOTE: These guidelines do not apply for groundwater systems. CSIR have separate guidelines for groundwater systems.

Basic CSIR surface water limestone contactor process description

In the basic CSIR surface water limestone contact process, the aggressive raw water is contacted with limestone pebbles in a fixed-bed reactor as shown in Fig. 1.

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The raw water is passed through a false bottom and percolates in an upward flow direction through a granite aggregate layer before entering a fixed limestone bed. The natural $CaCO_3$ dissolution driving force of the water (reflected by the calcium carbonate dissolution potential or CCDP) is used to take up calcium and carbonate species by exposing the water to graded particles of potable water grade stabilisation limestone ($CaCO_3$). In this manner, alkalinity, calcium and pH can all be increased to effect partial stabilisation. Thereafter the partially stabilised water flows out through a bell-mouthed spillway to a reservoir.

To date the installation of municipal-sized limestone contact units has been limited to the Western Cape, but construction of 100 Mℓ/d limestone contactors in the Free State province is underway, and pilot-plant verification of the suitability of the process has occurred for the soft waters of the Kunene, Kovango and Zambezi rivers in northern Namibia. Table 1 provides a list of limestone contactors installed at towns in South Africa.

NOTE: In order for the reader to have an idea of the relative size of a limestone contactor, two examples are presented in Fig. 2. The left of Fig. 2 indicates the installation at Rozendal (6 Ml/d) consisting of two identical cylindrical limestone contactors, of

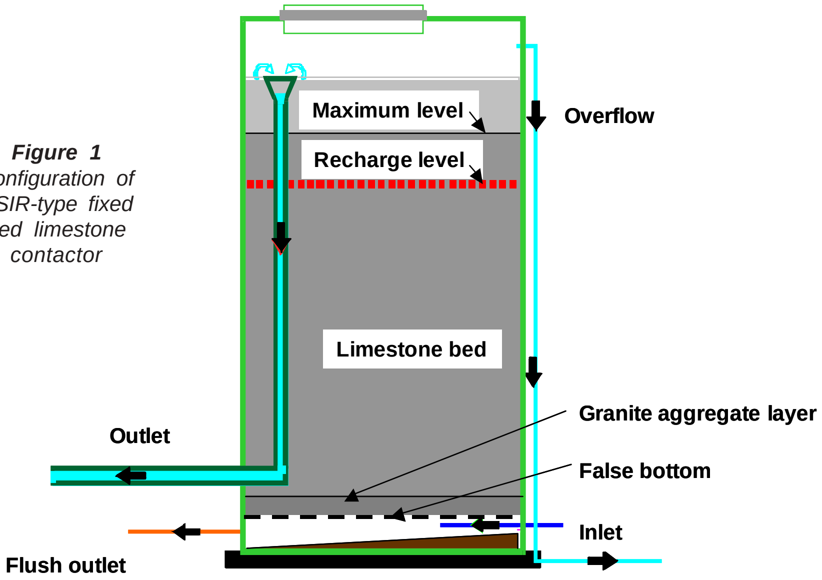

Figure 1
Configuration of CSIR-type fixed bed limestone contactor

TABLE 1
Operational surface water limestone contactors in South Africa

Unit location	Flow rate (Ml/d)	Raw water characteristics
Franschhoek WTW	2.5	Filtered, chlorinated, mountain catchment water
Jonkershoek, Stellenbosch	2.5	Chlorinated, mountain catchment water
Napier	2	Blend of untreated surface and groundwater
Montagu	3.8	Fully treated surface/dam water
Montagu Extension	5.6	Fully treated surface/dam water
Porterville	4	Filtered, chlorinated mountain catchment water
Bredasdorp	4.8	Fully treated dam water
Rozendal, Stellenbosch	6	Filtered, chlorinated mountain catchment water
Villiersdorp	3.5	Untreated surface and mountain catchment water
Wellington	10	Filtered, chlorinated mountain catchment water
Idas Valley, Stellenbosch	18	Filtered, chlorinated mountain catchment water

Figure 2
Rozendal (6 Ml/d) and Jonkershoek (2.5 Ml/d) limestone contactors

Figure 3
"Open to atmosphere" limestone contact unit showing algal growth

height 5.1 m and diameter 4.5 m. The right of Fig. 2 indicates the installation at Jonkershoek (2.5 Ml/d) consisting of two identical cylindrical limestone contactors, of height 4.1 m and diameter 3.9 m.

Generally, the use of limestone contactors has proven very effective in bringing about cost-effective partial stabilisation in distribution networks where otherwise no stabilisation would have been achieved (Mackintosh et al., 1998b). Significant improvements in drinking-water quality, and reduction in distribution network aggressive and corrosive attack have been achieved. Furthermore, since the first limestone contactors were designed and installed, considerable cumulative design and operational experience has been gained by the CSIR. On the counter side, instances exist where either poor design or poor operating practices have resulted in problematic or non-effective limestone contactors.

Surface water limestone contactor design considerations

CSIR limestone process developments originated in laboratory-scale work progressing to pilot scale work and eventually to full scale implementation. During all of these three stages CSIR considered the following **main design objectives**:

- **Minimising retention time requirements** (e.g. consideration of limestone type and particle size, quality of water fed to system, etc.).
- **Maximising contact efficiency** (e.g. prevent "dead" zones, ensuring equal flow to units, etc.).
- **Minimising operator input requirements** (e.g. use of piezometers to measure pressure drop, easy access to units for maintenance, etc.).
- **Prevent deterioration of water quality** (e.g. consideration of flow velocity in limestone contactor, mineral content of limestone, structure closed from sunlight, etc.).
- **Economic efficiency** (e.g. consideration of shape and size of units, number of units, material of construction, etc.).

CSIR surface water limestone contactor design guidelines

Based on the above basic design objectives, practical experience gained from operation and maintenance of full-scale limestone contactors, and practical observations gathered during site visits to the limestone contactors described in Table 1, CSIR developed the following guidelines for surface water limestone contactor design.

Generalised CSIR surface water limestone contactor design guidelines

- Cylindrical configuration, with ratio of limestone bed height to unit diameter of at least 1:1 (i.e. height always greater than diameter).
  - If a special motivation for departure from cylindrical units exists (e.g. rectangular limestone contactors), the hydraulics of the system must be very carefully considered. In particular it will be necessary to maintain the ratio of height to wall length of at least 1:1 and to bench the corners of the limestone contactors. The benching curvature should be placed to a minimum of one quarter of the wall length (i.e. if the wall has a length of 2 000 mm, the curved benching must be at least 500 mm).
- A minimum limestone bed depth of 2 m and a minimum clear water depth of 0.2 m are required to ensure efficient down flushing of the limestone bed.
- Completely enclosed structure, with access hatch on top for limestone addition.
  - It is important that the limestone beds be closed to the atmosphere. This protects both the limestone bed and final treated water from air-borne contamination, light penetration, algal growth, etc. Where units are open to the atmosphere significant problems with regard to bio-fouling and algal growth have been observed. This is clearly shown in Fig. 3.
  - All except one of the limestone contactors installed to date are constructed of cement-concrete. However, two limestone contactors constructed from fibreglass have operated successfully for a period of approximately 4 years.
- Use of a false bottom feed system (in preference to manifold / slotted pipe or other type systems).
  - Long-term operation of limestone contactors has shown that a false bottom distribution system is required as manifold or slotted pipe distribution systems are vulnerable to failure.

- At least two contactor units per installation (so that one unit can be decommissioned for maintenance while the other unit is still operational).
- Required limestone contact time to be not less than 20 min unless determined to be otherwise on-site.
- Loading rate to be no greater than 10 m/h.
- Two piezometers on each unit to measure pressure loss across the limestone bed.
  - Piezometers indicate pressure loss across the limestone bed, and are the only tool available to the limestone contactor operator to indicate when "down flushing" of insoluble fines is required.
- Piping to and from the units should be such that each separate unit must be able to:
  - Operate independently.
  - Be filled independently, with overflow "high turbidity" wastewater discharged to waste.
  - Be flushed to waste in both an upflow and downflow mode (flushing of silica and limestone fines). The ability for units to be isolated from each other whilst carrying out both "down flush" and "up flush" procedures to waste independently is strongly recommended.
  - Handle excessive flow loading via an overflow pipe to waste.
  - Be decommissioned whilst the other unit remains operational.
- Location of the limestone contactor in the treatment chain is an important consideration. Clarification, filtration and chlorination should take place before the limestone contactor. Furthermore pre-stabilisation iron levels should be < 0.1 mg/l, aluminium levels to be < 0.15 mg/l and turbidity < 1 NTU.
  - The limestone contactors have been developed to handle iron levels < 0.1 mg/l, aluminium levels < 0.15 mg/l and turbidity < 1 NTU. It is therefore essential that the limestone contactors are located after normal coagulation, flocculation, settling, filtration and disinfection processes. It must also be noted that coagulation and chlorination processes depress pH and that it is therefore important that these processes occur ahead of limestone stabilisation.
  - In instances where the limestone contactors have not been placed after general water treatment processes, the performance of the limestone contactors has been observed to be substandard with poor stabilisation efficiencies, excessive fouling and unwanted micro-organism growth occurring (see Fig. 3). Continued operation will eventually lead to failure of the limestone contactors.
- Heavy-duty high quality valves to be used at all times.
- Only limestone verified by CSIR as suitable for drinking-water stabilisation to be used. At present this is limited to "Aquastab Pebbles" supplied by P&B Limeworks, Bredasdorp.
  - Historically, limestone contactors have failed as a result of the use of inappropriate limestone media. When research into the use of limestone was initiated by CSIR, approximately 8 limestone deposits were evaluated. From this investigation, only the limestone mined by P&B Limeworks, Bredasdorp was found to be appropriate for potable water stabilisation. This limestone can be classified as a high calcium (and low magnesium) limestone. It is of a friable nature, highly soluble and with low insoluble silica, iron and manganese. The commercially available "Aquastab Pebbles" have a grading of +12 mm -15 mm and are currently delivered in either 25 kg or 1 t bags. In most cases the small bags are used for general topping up (easier to handle), whilst the 1 t bags are used for commissioning of the units or when significant addition of limestone is required. The 1 t bags have the advantage that their use results in the production of fewer fines during transport and handling. The bagged limestone should be kept in a store protected from the environment, including protection from direct sun light and moisture.
- Consideration should be given to protection of lower internal wall from aggressive and abrasive attack (e.g. use of an epoxy coating).
- Sample taps should be provided for both pre- and post-stabilisation water quality monitoring.
- Ensure equal flow into all limestone contactors, and ensure that flow into limestone contactors is not beyond maximum design capacity.
- 150 mm deep, 25 mm diameter granite aggregate between limestone bed and false floor system.
- An easily visible indicator (e.g. a painted line), showing the maximum and minimum limestone levels to be maintained in the limestone contactor, must be included.
  - The minimum limestone level indicator should be located at approximately 90% of the maximum limestone bed depth (i.e. if the maximum limestone bed depth is 5.0 m, the minimum limestone level should be 4.5 m). These indicators assist operators in determining when limestone recharge is required.
  - Limestone recharge is carried out when the limestone level in the contactor has dropped to the indicated minimum level. Limestone is manually added to the top of the limestone bed until it reaches the indicated maximum level. In most cases limestone is added using 25 kg bags. Some of the more recent larger units include a gantry to enable limestone recharge with 1 t bags. After limestone recharge, and the concomitant increase in water turbidity resulting from limestone fines, water is allowed to run to waste in an "up flush" manner until turbidity is regarded as acceptable.

Generalised CSIR operational, safety and maintenance guidelines

- Formal steps and railings to access lid and roof area to be provided.
  - Clearly, safe operator working environment is important and it is therefore necessary that proper access and safety railings must be provided.
- A gantry loading facility is preferable for limestone addition.
- Down-flushing of fines to waste should take place at least once a month, until site-specific required frequency is determined.
- Pre- and post-stabilisation water quality levels should be monitored on a regular basis.
  - Although the limestone contact process requires very little management, it is important to regularly monitor both the water quality prior to and after stabilisation so as to determine whether the units are operating effectively. Such practices also allow for easy and timeous detection of possible problems originating in the drinking-water treatment system, which may affect the operation of the limestone contactor.
  - A typical problem originating from inadequate water quality monitoring occurs where coagulation, using ferrous or aluminium salts, is practised. It has been observed that where residual iron/aluminium removal efficiency in the normal water treatment process is poor (originating from

sub-optimal operation of the water treatment works) it is not always reacted upon, as the limestone contact units were effective in removing the residual metal concentrations. In one extreme case resulting from significant problems with the water treatment plant, the limestone beds were used for final residual iron removal for a period of about six months. The resulting precipitation of iron in the limestone contactors necessitated eventual removal and replacement of the entire limestone media bed. In general, this approach is poor practice as the limestone contactors are not designed for this purpose, and it leads to fouling of the limestone beds.

- A record of the water quality and operation actions should be kept in a limestone contactor logbook.
  - In many instances formal operating procedures are not available or not used by the plant operators / technicians. In addition, in most cases formal logbooks were not maintained. It has been shown that if regular inspection and maintenance of the limestone contactor units does not occur, stabilisation efficiency will decrease.

Surface water limestone contactor commissioning procedures

Limestone loading and flushing

During the loading of the limestone it is important to minimise formation of limestone fines, and to flush existing fines to waste. During the initial loading and flushing, the product water of the limestone contactor (LC) will have a "milky yellow" appearance, which will eventually clear. The following procedure should be satisfied on a unit-by-unit basis:

- Begin by filling the first limestone contactor (LC) with the treated drinking-water which requires stabilisation, and maintain the flow rate through the unit at the maximum available and hydraulically permissible flow rate (i.e. at least the design flow rate, and preferably higher). LC operating in "upflow" configuration with final water flowing to waste.
- Once the LC is half full with water, initiate addition of the 1 t bags of P&B Aquastab pebbles. Maintain the flow of water through the LC (at the maximum available upward flow rate), with final water flowing to waste. Load limestone until the LC is one quarter full with limestone.
- Once the LC is one quarter full with limestone, stop loading limestone and check that the LC is filled with water, and "down-flush" the limestone bed ensuring that the "flush water" flows to waste. Re-fill the LC with water, and again "down flush" to waste for a total of four "down-flushes". Thereafter, fill the LC with water in the usual up flow manner and then allow the limestone bed to be "up-flushed" until the turbidity clears, or for at least 10 min. The final water must flow to waste.
- On completion of the "up-flush" add limestone to the water filled LC until the LC is half full with limestone; again whilst filling is taking place, maintain the flow rate at the maximum available upward flow rate. The final water must flow to waste.
- Once the LC is half full with limestone, stop loading the limestone, check that the LC is filled with water and "down-flush" the water to waste. Re-fill the LC with water, and again "down flush" to waste for a total of four "down-flushes". Again, thereafter the limestone bed is to be "up-flushed" until the turbidity clears, or for at least 10 min. The final water must flow to waste.
- On completion of the "up-flush", add limestone to the water filled LC until the LC is three quarters full with limestone. Again, whilst filling is taking place, maintain the flow rate at the maximum available upward flow rate. The final water must flow to waste.
- Once the LC is three quarters full with limestone, stop loading limestone, check that the LC is filled with water and "down-flush" the water to waste. Re-fill the LC with water, and again "down-flush" to waste for a total of four "down-flushes". Again, thereafter the limestone bed is to be "up-flushed" until the turbidity clears, or for at least 10 min. The water must flow to waste.
- On completion of the "up-flush", add limestone until the LC is full with limestone (i.e. to the "maximum limestone depth indicator"). Whilst filling is taking place, maintain the flow rate at the maximum available upward flow rate. The final water must flow to waste.
- Once the LC is filled with limestone to the indicated maximum, stop the loading limestone. Check that the LC is full with water and "down flush" the water to waste. Re-fill the LC with water, and again "down flush" to waste for a total of two "down-flushes". At the end of this cycle of flushing, re-initiate "up-flow" at normal design flow rate but with flow of water to waste. Run to waste for at least 2 h and until turbidity appears acceptable to the naked eye.
- The turbidity of the water leaving the LC must be measured. If turbidity is acceptable, water can be added to distribution network.
- Once the first LC unit has been successfully commissioned, the procedure can be repeated for each LC unit.

Additional important requirements

- At no stage in the above procedure should ANY water be passed into the drinking water system.
- At all times the limestone bed must be kept flooded (Obviously this does not apply during the down flush process). This is especially vital once loading and flushing have been completed.
- If the above-described procedure is not carried out carefully and thoroughly, "hydraulic shocks" to the units will result in turbidity problems in the final water that could be present for several months of operation.
- Once it has been confirmed that the turbidity is low enough for water to be passed into the water distribution network, it is the responsibility of the plant operators to ensure that the units are handled appropriately so that no "shocks" to the system result in increased turbidity.

Discussion and conclusions

In all cases the limestone contactors improved the aggressive/ corrosive qualities of their feed waters, and in most cases, significantly so. However, in a number of cases, operation of the units was not optimal, resulting in a poorer performance than expected.

Poor performance of limestone contactors can generally be attributed to the following factors:

- Feed water into the limestone contactor units does not meet acceptable drinking-water quality requirements (SABS 241 – 2001 Class 1). In most cases this is either due to the ineffective operation of the treatment processes prior to stabilisation or the incorrect positioning of the limestone contactor (i.e. before any treatment – the limestone contactor stabilises raw water). In general, problems relating to feed water quality not meeting acceptable standards were due to increased iron, aluminium and turbidity levels.

- The limestone beds are not cleaned (drained / flushed) on a regular basis. This results in the accumulation of sludge on the limestone pebbles that inhibits the dissolution of calcium carbonate into the water. Ineffective draining / flushing of the limestone bed may also be as a consequence of a poorly designed bed. Cylindrical units are generally of greater height, thus allowing more head (pressure) for flushing the limestone bed.
- Inadequate limestone contact time is allowed. This occurs as a result of not operating the bed at its designed limestone level, or exceeding the design capacity of the unit.
- The process is being used for non-intended purposes such as the removal of iron, turbidity and/or tastes and odours.
- Inadequate isolation from sunlight and air-borne contamination for the prevention of biological and algal growth.

In addition, a number of general operation / maintenance points are of relevance:

- Experience has shown that false-bottom water distribution systems are more robust than units having a slotted pipe configuration; thereby ensuring better long-term performance.
- In many instances formal operating procedures were not available or not used by the plant operators/technicians. In addition, in most cases formal logbooks were not maintained. This results in a lack of regular inspection and maintenance, which are necessary for efficient stabilisation.
- In all limestone contactor units visited the limestone used was Aquastab Pebbles, supplied by P&B Limeworks, Bredasdorp. Limestone was delivered in either 25 kg or 1 t bags, with 25 kg bags often used for general "topping up" purposes, and 1 t bags for unit commissioning.
- Water quality monitoring practices are often very poor. It is important to monitor the water quality both prior to and after stabilisation, to assess whether the units are operating effectively. Such practices also allow for easy detection of possible problems in the treatment system, which may affect the operation of the limestone contactor units.

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References

MACKINTOSH GS, DE VILLIERS HA, DU PLESSIS GJ, LOEWENTHAL RE and KORNMüLLER U (1998a) Stabilisation of Soft, Acidic Waters with Limestone. Report to the Water Research Commission, WRC Rep No 613/1/98.

MACKINTOSH GS, DU PLESSIS GJ and DE VILLIERS HA (1998b) Limestone mediated stabilisation for small water purification works. Paper presented at WISA Biennial Conference May 1998, Cape Town.