30th WEDC International Conference, Vientiane, Lao PDR, 2004

PEOPLE-CENTRED APPROACHES TO WATER AND ENVIRONMENTAL SANITATION

Low-cost defluoridation of water using broken bricks

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A low cost domestic defluoridator has been developed by the National Water Supply & Drainage Board of Sri Lanka to remove excess fluoride in drinking water to avoid endemic Fluorosis. Broken pieces of freshly burnt bricks are used as filter media in these units. A kinetic model for fluoride uptake in the filter with broken bricks as defluoridating agent is considered and the model parameters are estimated using experimental data. Data concerning the uptake of fluoride on broken brick pieces are obtained from water in batch in the defluoridator. The reaction rate parameter, k, and the capacity parameter fm are estimated and the model fits the collected data satisfactorily. fm is estimated to 0.10 mg/g and k which is a function of initial concentration varies between 0.001 and 0.0005 L/ (mg.ho.5) for low and high initial concentration. Broken bricks could be used as filter media for concentration of fluoride in raw water around 2 mg/1.

Introduction

Environmental fluoride has received much attention on account of the fact that an optimum concentration was found to reduce the incidence of dental caries. Low levels of fluoride are required for humans as it has beneficial effects on tooth and bone structures. However ingestion of excessive fluorides, mainly through drinking water causes dental and skeletal fluorosis (WHO 1970). The chronic toxicity by excessive fluoride intake has long been observed as skeletal abnormalities. The most common manifestation of the toxicity of fluoride in drinking water is dental fluorosis. Long-term ingestion of excessive fluoride has a chronic effect on the kidneys as well. The optimum level suggested by WHO is 0.7 mg/ L from infancy to 16 years. Fluorosis is related to the geology and climatic conditions of the place and the levels of fluoride. There is a distinctly geographical pattern in the incidence of fluorosis in Sri Lanka. The fluoride rich and fluoride poor areas have been demarcated and are closely linked with climate and geology. Geochemical surveys on the fluoride content of groundwater in Sri Lanka reveals that in the dry zone areas in Polannaruwa and Anuradhapura in the North-central province, Uda-Walawe and Wellawaya in the Southern Province and in Maho have high fluoride content (Dissanayake (1979)). High fluorides are in the plains especially in the dry zone, while the low fluoride areas are in the central high lands and in the western plains where the rainfall is high. With the rainfall fluoride is leached from rocks and soils and carried away in solution whereas in the dry zone evaporation causes upward capillary action of fluoride ions. The fluoride content of water obtained from lakes, artisan wells and rivers is mostly below 0.5 mg/L. Several defluoridation methods have been known to remove the excess of fluoride in drinking water to avoid endemic Fluorosis. Some of these methods are not suitable for rural communities in regions where the groundwater is fluoride rich; as they are not sustainable in those socio-economic conditions. A low cost domestic defluoridator was developed by the National Water Supply & Drainage Board of Sri Lanka and was tested in several villages in the dry zone using over thousand domestic units.

Prevention of fluorosis

Dental fluorosis is irreversible and therefore treatment is sophisticated and expensive. Thus the prevention of fluorosis is best and is the only form of treatment in Sri Lanka. Excessive fluoride content of water can be reduced to a desired limit by precipitation and adsorption. The adsorption method involves the contact of the fluoride containing water with a suitable adsorbent. Various substances such as activated carbon, activated alumina, activated bauxite, zeolite, hydroxyapatite etc.., have been used for fluoride removal from water (Choi et al (1979)). The ion-exchange, adsorption and precipitation are the usual means of defluoridation. However, most of the available materials for defluoridation are expensive and technically non-feasible in rural communities in Sri-Lanka. Hence the need to find locally available defluoridation media for safe and easy use at both household and small community level is desirable. National Water supply and Drainage Board has distributed low cost defluoridators among people in the affected areas. Easily available, Laterite or freshly burnt bricks broken into pieces has been used as filter media. Upward flow technique has been used to get more retention time. The performance of the sampled defluoridators has been monitored at regular intervals to see how well they are functioning. It was observed that at certain sites the desired effluent qualities were not obtained. In this study various factors affecting the defluoridator media is looked into and fluoride uptake in broken bricks as defluoridator media was modeled from experimental data.

Objective

The objective of this study is to determine the suitability of broken bricks as filter media of the low cost domestic defluoridator. This is achieved by determining the following model parameters related to the broken bricks:

- Capacity parameter for fluoride in broken brick pieces.
- Reaction rate parameter.

Model description

There have been various attempts to establish mathematical models to describe the fluoride uptake in a defluoridating agent, in the past five decades. Initially let us consider following three models from research studies done on various defluoridating agents.

-Larsen (1974), using dental enamel and Bhargava et al (1991), using bone char, described the uptake as a simple first order process kinetics to fluoride concentration in water (S) as described by:

$$\frac{dS}{dt} = -k_1 S$$

-Christoffersen et al (1984), described the uptake as first order with respect to the fluoride concentration in water and with respect to fluoride saturation deficit (fm –f) in defluoridating agent namely, Synthetic Hydroxy Apatite (Hap) as given by:

$$\frac{dS}{dt} = -k_1.X_{DA}\left(f_m - f\right)S - k_2 X_{DA} f$$

- Stumm (1992) used a semi- infinite linear diffusion limited sorption in porous media in general, where uptake is proportional to concentration of fluoride in water and dosage of defluoridating agent and also the reciprocal of square root of contact time as given by:

$$\frac{dS}{dt} = -k.X_{DA} S.t^{-0.5}$$

These tested models fit some of the data collected, but none of them seem to fit in general, for all the different experimental conditions. Therefore the development of a general model to describe the change in fluoride concentration in water in batch as a function of time by mean of an explicit mathematical equation was envisaged by Bregnhøjet al (1995) and is described in the following section.

A kinetic model to describe fluoride uptake in batch

Bregnhøj et al (1995) developed a model to address the situation of treatment of water in fluoride affected areas in developing countries. So the number of experimental variables and rate parameters were to be kept as few as possible and advanced characteristics of the filter media such as bulk density, grain size, particle spherity etc…, were to be avoided. The following differential equation to describe

$$\frac{dS}{dt} = -k.X_{DA}\left(f_{mb} - f\right)S.t^{-0.5}$$

the change of fluoride concentration was thus developed by Bregnhøj et al (1995) using trial and error approach with many different models.

As f is the concentration of fluoride up taken in the defluoridating agent and fm is a measure of maximum concentration of possible uptake, (fm -f) would represent a deficit towards saturation of defluoridating agent (DA). Where XDA is the mass of defluoridating agent per liter of water in the filter. Thus X.DA (fmb -f) is the total potential uptake per volume of defluoridating agent. This equation express that the rate of fluoride uptake is first order with respect to the fluoride concentration in water S, first order with respect to saturation of defluoridating agent XDA (fmb -f), as well as first order with respect to inverted square root of time(t-1/2). This model seems to fit various defluoridating

$$f = \frac{\left(S - S_0\right)}{X_{DA}}$$

media. Assuming that the initial concentration of fluoride in the defluoridating agent is negligible (f=0), f may at any

$$S = \frac{X_{DA}.f_{mb} - S_0}{\left[\frac{X_{DA}.f_{mb}.e^{2k\left(X_{DA}.f_{mb} - S_0\right)t^{0.5}}}{S_0} - 1\right]}$$

time be given as,

$$\beta = \frac{X_{DA} f_{mb}}{S_0}$$

By Substituting into the equation, concentration of fluoride

$$S = \frac{S_0\left(\beta - 1\right)}{\left(\beta.e^{2.(\beta-1).S_0.k.t^{0.5}} - 1\right)}$$

in the water is given as a simple function of time.

Let β be expressed as

Then equation (6) be expressed as

Thus the S-t curve of uptake of fluoride in a defluoridating agent (DA) is characterized by only two parameters ß and k., for a given defluoridating agent, these parameters could be determined by an optimization technique.

Application of kinetic model on low cost defluoridating materials

Simple inexpensive method of fluoride removal has been the quest for many years. The general requirement for household defluoridation methods are:

1. The required capital investment should be modest and should be affordable by the affected community.
2. The maintenance cost of the method should be low.
3. It should be simple in design and the villagers should be able to operate it.
4. The method should be able to reduce the fluoride content to low levels within a day or so and should improve the quality of water in general.

Clay being an indigenous and inexpensive material in the high fluoride regions the fluoride binding potential of clay and clayware were investigated by several researchers.

The effect of firing temperature

As important factor in the choice of clayware as defluoridating agent is its firing temperature. The firing of clays causes a series of physical and chemical changes in the material. Free water in clay is driven off by gently increasing the temperature to about 100 0C. Chemically bonded water namely water of crystallization escapes at 400 0C to 550 0C. Change in crystalline structure of clay mineral take place about 350 0C.Carbonaceous matters in clay is burned out at 800 0C to 900 0C. Haunge et al (1994) examined the efficiency of clay pots and crushed clay pots in removing fluoride from water. In the experiments fluoride adsorption declined as the firing temperature increased and when heated above 800 0C pots were rendered unfit for defluoridation purpose.

Methodology

Typical low-cost domestic defluoridator, distributed by the National Water Supply & Drainage Board is shown in Photograph 1.

Raw water is poured in through the funnel attached to 25 mm diameter PVC pipe which runs to the bottom compartment. Thus raw water enters the defluoridator through the bottom compartment and moves upward as the water was removed from the top. The defluoridator has a capacity of about 16 L and this quantity of water could be used by a household for cooking and drinking purposes.

Experimental Run

Two sizes of brick pieces were used for the experiment in two separate filters. The size of particles, initial concentrations and weight of the batch of brick pieces is given in Table 1 and 2. Three trials were down using both filters. A third trial

Table 1 Sizes of filter media.

Parameter	Filter	
	F1	F2
Particle size (mm)	12 – 16	5 – 8
Volume of Raw Water (L)	17	16

Table 2. S_0 and X_{BP}

Parameter	Trial No		
	1	2	3
Initial Fluoride Concentration (mg/L)	6.2	6.25	2.0
Weight of the batch of bricks (kg)	25.460	27.695	24.460

Photograph 1. Low cost defluoridator

Table 3 Measured and estimated concentrations

Retention time (hours)	Estimated fluoride Concentration (mg/L)	Measured fluoride Concentration (mg/L)
0	2.00	2.00
0.5	1.37	1.44
1.0	1.17	1.24
1.5	1.03	1.10
2.0	0.94	0.81
3.0	0.79	0.79
3.5	0.64	0.63
4.0	0.57	0.59
4.5	0.51	0.49
5.5	0.50	0.50
7.0	0.50	0.50
24	0.14	0.25
27	0.12	0.20

was down using a new batch of media of particle size 12-16 mm with low initial concentration. Water and bricks used were brought from fluoride rich area and initial concentration of fluoride in water was 6.0 – 6.5 mg/l. The fluoride concentration and contact time were recorded. Fluoride in water was analyzed using the direct reading DR / 2000 HACH spectrophotometer.

Results

Parameters ß and k were estimated using the method of least squares. Substituting the estimated parameters in the model, concentration of fluoride in water can be estimated for corresponding contact time. The estimated concentrations satisfactorily fit the measured concentrations and it is shown in figure 1.

Table 4. Kinetic model parameters for broken brick pieces as defluoridating agent.

Description	Trial		
	1	2	3
Broken Brick Size (mm)	12-16	5-8	12-16
Initial concentration S_0 (mg/L)	6.20	6.20	2.00
X_{BP} (g/L)	1593.75	1846.23	1591.25
ß	37.23	42.50	81.25
f_m (mg/g)	0.145	0.167	0.102
k(L/mg.$h^{0.5}$)	0.00067	0.00064	0.00165

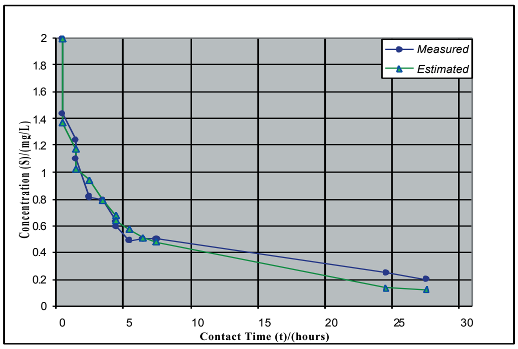

Figure 1. Measured and estimated concentration of fluoride

Conclusions

- The capacity parameter fmb mainly depends on quality of bricks, especially the firing temperature of bricks and the optimal range is between 500°C and 700 oC. The reaction parameter 'k', which depends on the initial concentration of fluoride (So) in raw water seems to decrease rapidly as So increases from 2.0 mg/L to 6.2 mg/L. Since bricks demonstrate poor fluoride removal quality for raw water containing high concentration of fluoride, they are not suitable as filter media to achieve the desired level of fluoride in the effluent under these conditions. Although the rate of removal of fluoride is better in smaller size of brick pieces as it has larger surface area for adsorption, water storage capacity decreases in the defluoridator with the decrease in porosity.
- The kinetic model can be extended to simulate the behaviors of low cost defluoridator under rural set-up. Thus the proposed extended kinetic model is a useful tool in the design and operation of low-cost defluoridators.
- It was assumed that the raw water was retained in the defluoridator for a day before consumption. Predicted quality of the effluent in the defluoridators for broken brick pieces as defluoridating agents seems to tally reasonably well with the measured data, in spite of various limitations encountered.

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Notes

Appendix I: Notations

The following symbols are used in this paper

f = Fluoride Concentration in Defluoridating Agent (DA)

fm = Capacity Parameter for fluoride uptake on a Defluoridating Agent (DA)

k = Reaction rate parameter (Lmg -1 h -0.5)

S = Fluoride Concentration in the water phase (mg/ L)

XDA = Dosage of Defluoridating Agent. (DA)

XBP = Dosage of Brick Pieces in filter.

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