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AN IMPROVED FILTER MEDIA TEST FOR TROUBLESHOOTING AND REHABILITATION OF PROBLEM FILTERS

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Abstract

A standard “floc retention test” was made available by the American Water Works Association¹ to provide a routine measure of filter media cleanliness. This would allow early detection of the potential for serious problems. The test is performed by preparing a 50g media sample and shaking it vigorously in 100ml of water. The resultant suspension is then decanted and, after five repetitions, the turbidity of the combined suspension is measured, doubled and reported as NTU (nephelometric turbidity units)/100g of sand. The turbidity, according to AWWA guidelines, ranges from < 60 (clean filters) to 300 NTU/100g (filters with a possible mudball problem)².

At many South African plants, filters appear to be inadequately cleaned by routine backwash procedures. The hypothesis is that the root of this phenomenon lies in the high degree of biological activity within filter beds. This presumably results in a sticky biofilm on the media grains, which is difficult to remove. The floc retention test proved to be an indispensable tool for a systematic survey of water filtration plants currently being carried out to test this hypothesis. To improve reproducibility and insight into the reasons for media fouling, the floc retention test was refined in a number of ways, which is the main focus of this presentation:

- Moisture content correction: Moisture content of filters is dependent on the time elapsed between draining and sampling and is highly variable (5 to 28%).
- Agitation by cylinder inversion vs. vigorous shaking: Tests determined that this method yielded lower values but resulted in more reproducible results.
- Gravimetric vs. nephelometric measurement of deposits: The former is less dependent on the nature of the particles in suspension.
- Splitting deposits in terms of acid solubility and volatility: This indicates the nature of the deposits (biological, chemical or inorganic).
- Measurement of the elemental makeup of deposits: The suspension is dissolved in acid and its elemental composition is measured.

The suggested refinements were put to the test during a survey of eight South African plants. Large differences in overall media cleanliness were found, ranging from 1 to 20 mg of deposits/g of media. It was, however, by splitting the deposits into different categories (acid-soluble, volatile and inert) where

the improved procedures came into their own. The volatile fraction (biological) ranged from 10 to 60% of the total solids, loosely corresponding to the eutrophic status of the raw water. The acid-soluble fraction (chemical precipitates) ranged from 1 to 79% suggesting improper pretreatment and/or poor backwashing. Where the elemental analyses showed significant iron and manganese concentrations (in addition to the ubiquitous presence of calcium and magnesium), it could directly be related to the raw water problems.

The refined floc retention test proved to be a significant improvement to the old, assisting operators in the detection of potential problems, understanding their nature, and suggesting focused solutions.

Introduction

Rapid sand filters are expected to continuously produce clean, safe water for many years and, in almost all South African water treatment plants, provide the primary barrier against protozoan cysts and oocysts. Many of these filters develop problems over the years, for example media losses, mudball formation, cracks in the bed and growth of chemical deposits on media grains, all leading to the gradual decline of the filter beds. However, these problems often only become apparent once the damage is done. It is, therefore, important that the cleanliness and overall condition of filters be tested on a regular basis using a routine measurement so that such problems may be either prevented or arrested.

The 'floc retention' test, made widely available by the American Water Works Association¹, was the first standardised procedure to provide such a routine measure, with benchmark values with which one could compare the performance of individual filters within a treatment plant. However, many water treatment plants in South Africa are fed by nutrient or biologically-rich waters due to the climatic conditions of the region. This led to problems in comparisons with the AWWA provided thresholds, despite the knowledge that the filters tested were of a high standard in terms of performance. In addition, many South African water treatment plants do not have access to sophisticated laboratory equipment necessary to perform this test accurately and, therefore, the need to develop a similar test that could be performed using minimal laboratory equipment, yet still be operator-independent and reproducible in terms of its results.

The focus of this paper is, therefore, to provide the details of an improved 'floc retention' test and how the results obtained can be used to indicate not only the cleanliness of a filter operated under South African conditions, but also to indicate the composition of the deposits on the media grains and suggest remediation strategies that can be applied to either overcome or arrest existent problems within the filter sampled.

Comparison of the AWWA test and the SA suggestions

The 'floc retention' test, as outlined by AWWA, was used extensively on surveys of South African filters for approximately two years and was found to be a most useful test with a good basis and practical application that was fairly easy to follow.

However, during this time three shortcomings of the test were identified with respects to the procedure. These shortcomings are outlined and addressed below³:

Moisture content:

Upon performing the AWWA test on media sampled during an initial survey of South African filters the Water Research Group at the Rand Afrikaans University found it difficult to obtain consistent moisture content for the various samples since this factor appeared to be highly dependent on the time and duration of draining of the various filters before sampling. This inconsistency was corrected by direct measurement of the moisture content. This was done by weighing an additional sample (taken from the same batch used to perform the 'floc retention' test) both before and after drying in an oven at 105°C. The following two equations could then be applied to incorporate moisture content and, thereby, provide a dry mass of the media tested:

$$MC = \frac{\text{mass before drying}(g) - \text{mass after drying}(g)}{\text{mass before drying}(g)} \dots\dots\dots [1]$$

$$\text{dry mass}(g) = \text{wet mass}(g) \times (1 - MC) \dots\dots\dots [2]$$

Turbidity measurements:

The measurement of turbidity in nephelometric turbidity units (NTU) posed some additional problems. Firstly, the NTU values were too high to be measured directly and a simple dilution factor equation was required:

$$DF = \frac{m\ell \text{ sample} + m\ell \text{ clean water}}{m\ell \text{ sample}} \dots\dots\dots [3]$$

$$NTU/100g = \text{measured NTU} \times DF \times \frac{100}{\text{dry mass}(g)} \dots\dots\dots [4]$$

Secondly, the results obtained would fluctuate quite significantly due to the scattering of light by larger particles and, by the time a stable measurement could be obtained, the deposits in the stripped suspension would have settled and the results would be skewed. This problem was partly overcome by taking six readings at 5 second intervals for a period of 30 seconds (starting at 5 seconds) and averaging the results obtained.

Thirdly, it was also difficult to interpret the results, since turbidity is influenced by the nature of the deposits in the suspension. It was, therefore, suggested that total suspended solids (expressed as mg of deposits per g of dry media) would provide a gravimetric measure of the suspension and, thus, eliminate this influence.

Procedure 209C of Standard Methods⁴ was, therefore, incorporated into the measuring procedure, with the application of equations 5 and 6 below on the results:

$$TS(mg/\ell) = \frac{\text{mass of dried residue}(mg) \times 1000}{\text{sample volume}(m\ell)} \dots\dots\dots [5]$$

$$mg/g \text{ sand} = \frac{mg/\ell}{200} \times \left(\frac{100}{\text{dry mass}(g)} \right) \dots\dots\dots [6]$$

Stripping procedure:

Further analyses of the tests performed on the media sampled during the survey indicated that the results yielded by the vigorous shaking method were difficult to reproduce. Therefore, a number of alternative procedures were investigated with consideration for improved reproducibility of results, as well as the establishment of benchmark values that would facilitate comparisons between filters.

Since many South African water treatment plants do not have access to sophisticated equipment for this test, a manual agitation method with minimum use of laboratory equipment would be best for application. Hence, the suggested improved procedure is detailed below:

- The media sample was placed in a 250ml measuring cylinder.
- 100ml of tap water was then added to the cylinder.
- The cylinder was then sealed and inverted 20 times (see figure 1 below) and the resultant suspension (or 'syrup') decanted into a clean 500ml Erlenmeyer flask:

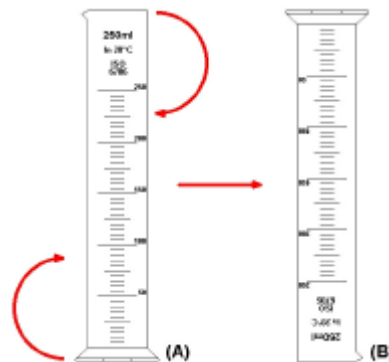


Figure 1: Illustration to show a single inversion of the measuring cylinder, i.e. from position (A) to position (B)³.

- This inversion-decanting procedure was repeated four more times to yield a 500ml volume of deposits suspended in tap water.

South African Survey of Treatment Plant Filters

Filters from eight South African Water Treatment Plants were sampled (two were sampled four times each, four were sampled three times each and two were sampled once) between May 2002 and July 2004. These plants were scattered in four provinces of South Africa, with the majority of samples taken in the spring-summer months. The types of media sampled varied between sand and sand-anthracite combinations. The types of raw waters supplying the plants sampled varied from eutrophic through turbid to low-turbidity waters.

Each filter was sampled both before and after a backwash was performed. In most cases, the filters were backwashed between one and four more times, with samples obtained following each backwash. In the case of six of the plants, an additional vigorous backwash was also performed using a test column either on site or in the laboratory, with samples taken after this wash. Each sample taken (with the exception of three) was tested three times for replication purposes, resulting in a total of 316 individual results.

Moisture content:

A single moisture content test was performed per sample for the correction of masses. The results obtained from the column wash samples are reported separately from those obtained directly from the filter, due to varying draining procedures between the *in situ* and laboratory conditions. Table 1 below shows the spread of both filter and column sample moisture contents.

Table 1: Variability of moisture contents (*in situ* and laboratory conditions).

	<i>In situ</i> /filter draining	Laboratory/column draining
Average	15%	20%
10 th percentile	5%	11%
90 th percentile	27%	30%

As can be seen from the spread of the results (10th and 90th percentiles), the moisture content is too variable a factor to exclude from the 'floc retention' test. The difference in averages and, more specifically, the lower range (10th percentile), of results obtained from the filter samples as compared with the column samples also indicate that the moisture content is dependent on the conditions of draining and sampling.

Relationship between turbidity and total suspended solids:

In order to illustrate the relationship between turbidity and total suspended solids per plant, turbidity results (taking into account dilution factors) were

plotted against those of total suspended solids for each plant. A trendline, with zero intercept, was then plotted to provide a NTU/TS ratio for each plant.

For both turbidity and total suspended solids, the moisture content factor was excluded from the results and, therefore, reported in NTU and mg/l to allow for an accurate comparison between the turbidity and total suspended solids of the sample analysed. Table 2 below summarises the relationship (as determined from the trendline equation) per plant.

Table 2: Relationship between turbidity (NTU) and total suspended solids(TS) (mg/l) per plant.

	NTU/TS ratio (F)	R ² value
Plant #1	0.54	0.88
Plant #2	0.65	0.55
Plant #3	0.48	0.88
Plant #4	0.77	0.91
Plant #5	0.70	0.67
Plant #6	0.96	0.90
Plant #7	1.11	0.85
Plant #8	1.05	0.46

Conversion of AWWA guidelines:

After deciding that total suspended solids was a better measure of the ‘cleanliness’ of the suspension, it was necessary to convert the AWWA turbidity guidelines into suspended solids (expressed in mg/g), to facilitate the comparison of results from subsequent tests.

This conversion was, therefore, facilitated through the use of the trendline equations for each plant (as shown in Table 2 above), equation 7 below, as well as the average moisture content (*in situ*). The results obtained were then averaged to obtain a result for each AWWA guideline value in mg/g (Table 3).

$$TS \text{ (mg/g)} = \frac{NTU/100g \text{ wet}}{200 \times F \times (1 - MC)} \dots\dots\dots [7]$$

Table 3: AWWA guidelines as total suspended solids (mg/g).

AWWA Guideline (NTU/100g wet)	300	120	60	30
Minimum TS (mg/g)	1.58	0.63	0.32	0.16
Maximum TS (mg/g)	3.71	1.49	0.74	0.37
Average TS (mg/g)	2.45	0.98	0.49	0.25

Guidelines from South African filter survey:

It was found that the results obtained from the South African filter survey were much higher than the AWWA interpreted guidelines, despite the knowledge that these filters were performing well by South African standards.

During each plant visit made during the survey, a visual assessment through observation of each filter was made with respects to backwashing procedures and the general condition of each filter sampled, in terms of “dead-spots”, existent mudball problems and overall effectiveness of backwashing. Whilst this assessment step was a qualitative rather than quantitative one, it assisted in the classification of each plant according to the AWWA four-point classification.

Each plant was classified as either (1) a clean bed, (2) a slightly soiled bed without cracks, mudballs and dead spots, (3) a filter with evidence of small mudballs, or (4) a filter with a obvious bed problems and high incidence of mudball formation. Following this classification step, the average total suspended solids (in mg/g) of the after-first-backwash samples were determined for each plant. Table 4 below summarises these results:

Table 4: Average TS and visual classification of filter beds after a single backwash cycle, with suggested classification limits.

	Classification	TS (mg/g)	
Plant #6	Media appeared clean	0.8	
Plant #3	Media appeared clean	2.0	
Plant #7	Media appeared clean	2.6	
Plant #2	Media somewhat dirty, no mudballs	4.0	← Set threshold A at 3 mg/g
Plant #8	Media somewhat dirty, no mudballs	4.1	
Plant #1	Small mudballs	7.5	← Set threshold B at 6 mg/g
Plant #5	Small mudballs	11.2	← Set threshold C at 10 mg/g
Plant #4	Definite mudball formation	19.5	
<i>Min.</i>		0.8	
<i>Max.</i>		19.5	
<i>Ave.</i>		6.5	

When comparing these threshold values to the equivalent AWWA guidelines (Table 3), it can be seen that this survey proposes less stringent guidelines than those of AWWA, i.e. values are in the order of four to six times greater.

Table 5 below shows the comparison between the AWWA guidelines (both turbidity and interpreted TS) and the SA guidelines:

Table 5: Comparison of AWWA² and SA guidelines.

	AWWA guidelines		Revised SA guidelines
	NTU/100g	mg/g	mg/g
Clean filter and ripened bed	30 – 60	0.25 – 0.5	<3
Slightly dirty, less than ideal bed, but not yet a concern	60 – 120	0.5 – 1.0	3 – 6
Dirty bed with need for evaluating the filter washing system and backwash procedure	120 – 300	1.0 – 2.5	6 – 10
Could indicate a mudball problem	>300	> 2.5	>10

Further Development of the Improved Test

In addition to knowing the quantity of deposits on the media, further knowledge of the nature of the deposits would provide insight into what specific problems an individual filter faces, as well as assisting in the suggestion of appropriate rehabilitation strategies.

Therefore, the total suspended solids test was extended in two ways to assist in identifying the various compositions of the deposits (biological, chemical and inorganic). The first facilitated the determination of what fraction of the deposits was acid-soluble, whilst the second facilitated the determination of what fraction of the deposits was volatile.

In addition an elemental analysis of each suspension was performed for between 16 and 18 elements, which may provide insight into known problems in the raw water feeding the filters.

Acid-soluble and non-soluble fractions:

The deposits in suspension were subjected to a 0.185M HCl solution for a minimum of two minutes. This was achieved by adding 10ml of a 6.4% HCl solution to 100ml of the suspension.

As with the total suspended solids determination step, Standard Method 209C⁴ was used and the results for total non-soluble suspended solids (NS) expressed in mg/g using equation 8 below, as well as equation 6 above:

$$NS(mg/\ell) = \frac{\text{mass of non-soluble residue}(mg) \times 1000}{\text{sample volume}(ml)} \dots\dots\dots [8]$$

Volatile and non-volatile fractions:

Standard Method 209D⁴ was applied to the filtrates from the total suspended solids and acid-solubility tests performed in the above steps to yield results for total non-volatile suspended solids (NV) and total non-soluble non-volatile

suspended solids (NSNV) (see equations 9 and 10 below). As in the previous two tests, the results are expressed in mg/g using equation 6 above:

$$NV(mg/\ell) = \frac{\text{mass of non-volatile residue}(mg) \times 1000}{\text{sample volume}(m\ell)} \dots\dots\dots [9]$$

$$NSNV(mg/\ell) = \frac{\text{mass of non-soluble non-volatile residue}(mg) \times 1000}{\text{sample volume}(m\ell)} \dots\dots [10]$$

The characterisation matrix:

The four values yielded by the three tests outlined above, were then placed into a matrix system that enabled the characterisation of the deposits in suspension through simple subtraction (see Table 6 below):

Table 6: Suspended solids composition matrix⁵.

	Soluble	non-soluble	Total
Volatile	<p>SV decomposition or volatilisation of some mineral salts (A - B - C + D)</p>	<p>NSV <i>bacterial and algal biomass, organic detritus</i> (B - D)</p>	(A - C)
Non-volatile	<p>SNV <i>originates from the carry-over of chemical precipitates</i> (C - D)</p>	<p>NSNV Equation [10] <i>corresponds to inorganic particles present in the raw water</i> D</p>	<p>NV Equation [9] C</p>
Total	(A - B)	<p>NS Equation [8] B</p>	<p>TS Equation [5] A</p>

Elemental analysis of deposits:

Inductively coupled plasma optical emission spectroscopy (ICP-OES) was used to determine the presence of between 16 and 18 elements in each suspension.

The results were expressed in mg/g as before using equation 6 and the results obtained from equation 2 for each sample. For reference purposes, the tap water used to strip the media was also analysed and the values subtracted from those of each sample to enable the determination of the composition of the deposits alone.

The elements analysed are listed in Table 7 below, along with their quantitative detection limits (the values below which detection becomes inaccurate). The four elements highlighted in the table (Ca, Mg, Mn and Fe) are those cations known to cause filtration problems and, therefore, of particular interest to this study.

Table 7: Elements and limits used for ICP-OES analysis.

Element	Limit (mg/l)	Element	Limit (mg/l)	Element	Limit (mg/l)
Calcium (Ca)	0.05	Cobalt (Co)	0.10	Sodium (Na)	0.10
Barium (Ba)	0.05	Cadmium (Cd)	0.05	Zinc (Zn)	0.05
Strontium (Sr)	0.05	Nickel (Ni)	0.05	Lithium (Li)	0.10
Magnesium (Mg)	0.05	Manganese (Mn)	0.02	Lead (Pb)	0.10
Copper (Cu)	0.02	Iron (Fe)	0.05	Bismuth (Bi)	1.00
Aluminium (Al)	0.10	Chromium (Cr)	0.05	Boron (B)	0.05

Results From Characterisation Analyses

Acid solubility and volatility of deposits:

The results of the acid solubility and volatility tests showed that the soluble and volatile (SV) fraction was not very significant (ave. 5%) and it is speculated that this fraction is probably biological in origin. Therefore, for the purposes of this interpretation, the non-soluble and volatile (NSV) and SV fractions are added together to get a single total volatile fraction (V), which represents the biological contingent of the deposits. The three values (NSNV, SNV, and V) are summarised in Table 8 below:

Table 8: Average composition of deposits per plant (in mg/g and %).

	Ave. TS (mg/g)	Composition per fraction characterisation					
		NSNV		SNV		V	
		mg/g	%	mg/g	%	mg/g	%
Plant #6	0.8	0.21	25%	0.18	42%	0.27	33%
Plant #3	2.0	1.47	73%	0.48	1%	0.53	26%
Plant #7	2.6	0.74	29%	1.22	20%	1.32	51%
Plant #2	4.0	0.35	9%	0.44	77%	0.55	14%
Plant #8	4.1	0.75	18%	1.43	42%	1.63	40%
Plant #1	7.5	1.92	26%	3.40	21%	4.02	54%
Plant #5	11.2	3.00	27%	0.97	61%	1.34	12%
Plant #4	19.5	14.71	75%	4.00	2%	4.34	22%
Minimum	0.8	0.21	9%	0.18	1%	0.27	12%
Maximum	19.5	14.71	75%	4.00	77%	4.34	54%
Average	6.5	2.89	35%	1.51	33%	1.75	31%

From this summary it can be seen that the composition of media deposits varies greatly between plants despite the averages being much the same. Plants 3 and 4, for example, have high inorganic deposits (natural silts), suggesting that mechanical cleaning methods would need to be employed to clean the media. Plants 2 and 5, however, have deposits consisting mostly of chemical precipitates, which suggests that an acid could be used to treat the media *in situ*. In the case of plants 1 and 7 the deposits are highly biological, though the inorganic and chemical contents are still significant, therefore, implying that *in situ* treatment with chlorine (Cl₂) would be most effective. Interesting to note is that plants 6 and 8 appear to yield deposits with a relatively uniform composition and, therefore, treatment of the media at these plants would need to be multifold.

Elemental analysis:

At the time of publication of this paper, the elemental analyses performed and reported below only represent those filters sampled up to October 2003. It is, however, expected that the additional results will not change the overall picture significantly, since existing problems are expected to remain unchanged.

The percentage composition of each of the four identified ‘problem’ elements was determined, by simply expressing it as a fraction of the sum of the mg/g of elements measured per sample. These results are summarised in Table 9 below:

Table 9: Composition of deposits in terms of four problem elements (in mg/g).

	Total suspended solids (TS) (mg/g)	Elements (mg/g)			
		Ca	Mg	Mn	Fe
Plant #6	0.8	0.194	0.051	0	0.003
Plant #7	2.0	0.309	0.069	0	0
Plant #3	2.6	0.120	0.059	0.006	0.011
Plant #8	4.0	0.391	0.078	0	0
Plant #2	4.1	0.182	0.055	0	0
Plant #1	7.5	0.246	0.080	0.007	0
Plant #5	11.2	0.262	0.057	0	0
Plant #4	19.5	0.154	0.072	0.220	0.047

As expected, the results show that calcium and magnesium are present in high quantities for all the plants. These two elements represent the harder scale-like precipitates present in the media deposits that are not easily removed by the stripping method used and, therefore, do not have a correlation with amount of solids (TS) deposited on the media.

There are, however, large differences in the quantities of manganese and iron in the samples. This correlates with known manganese and iron problems in the raw waters of the plants in which these elements were detected. Although the stripping method used was able to strip these deposits from the media, the

normal backwash procedures did not, implying that the backwash procedures currently used for these plants are inefficient and need to be more aggressive.

Discussion and Conclusion

This investigation led to a number of conclusions regarding the testing of filter media and the reporting of results to provide meaningful insight into the performance of each filter as well as potential problems:

A standard test was developed that proved to work well in practice:

- It made use of a moisture content factor that made results more comparable to each other.
- The results obtained were reported based on a mass concentration, rather than a visual one, providing a better measure of filter media cleanliness.
- It provided a method of stripping filter media of deposits that was reproducible and made use of basic laboratory equipment that could be easily obtained by any treatment plant.
- The sample yielded by the improved test could be used to provide information about the nature of the deposits on the media, which would suggest suitable rehabilitation strategies in turn.

Based on the survey of this investigation, new threshold guidelines were suggested, which are significantly higher than the comparable AWWA guidelines.

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