PRACTICAL GUIDE FOR THE OPTIMISATION OF COAGULATION-FLOCCULATION THROUGH JAR TESTING

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ABSTRACT

The presence of algae, cyanobacteria and organic matter in raw water can present a significant challenge for water treatment plant (WTP) operators. Sedimentation and floatation operations preceded by coagulation-flocculation (C-F) are reliable processes for separating these contaminants. They are often the major barriers to these contaminants entering drinking water supplies. C-F can be challenging to optimise as a result of highly variable conditions that can affect the C-F process. This can include hydrodynamic conditions, temperature, pH, coagulant type, organic matter composition and, in the case of algae and cyanobacteria, cell growth phase, population density and morphology. Turbidity breakthrough, membrane fouling, filter clogging and ineffective disinfection have been associated with unsuccessful upstream C-F.

Jar testing is a method that simulates the C-F process and can provide helpful data to help operators to optimise performance. Disadvantages of jar testing are that it can be time-consuming and require technical knowledge to assess the results. However, jar testing can be a powerful tool to save money and enhance water quality as it helps determine which treatment chemical and dose will work best with their WTP's raw water.

This jar testing practical guide was developed and includes experiment set-up, operational procedure and data analysis to assist operators in overcoming the main constraints of jar testing.

1.0 INTRODUCTION

Jar testing is the most widely used process for determining coagulant dose for reducing turbidity, algae and organic matter in raw water used for drinking purposes. Jar testing is a powerful tool with little operational expenditure that can enhance water quality by helping determine which treatment chemical, dosage and dose will work best with a system's raw water. However, jar testing procedures can be time-consuming for operators, may not provide the necessary data to make informed decisions on the selected coagulant type and dose for transferable full-scale plant performances, and does not allow adjustment of coagulant dose rates to keep pace with rapidly changing raw water quality.

The constraints of jar testing can be overcome if there is a protocol that guides the operators to conduct this testing in an efficient way. This paper describes a guide for the operators to make jar testing an excellent tool for treatment optimisation.

2.0 DISCUSSION

A successful jar testing procedure must include all the relevant steps that imitate the coagulation, flocculation and settling or floatation so it can predict the performance of the plant. The following steps are recommended based on the experience of performing more than 100 jar testing experiments. The steps can be individually tailored to predict the performance of the water treatment plant.

STEP 1: DEFINE THE PURPOSE OF JAR TESTING

Defining the purpose of jar testing as a first step can reduce the testing time as it can define the coagulant dose range to be tested.

There are two common objectives of carrying out jar testing

1. To fine tune the coagulation dose and pH
2. To determine optimal coagulant doses due to change of raw water or treated water quality

If fine-tuning the coagulation dose, the coagulant dose range tested should be not vary more than 20% from the current dose of the plant. If determining the optimal dose due to a change in raw or treated water quality, the coagulant dose range tested should vary more than 20% from the current dose.

STEP 2: COLLECT SAMPLE OF RAW WATER

Raw water can change profoundly on a seasonal basis. These changes could arise from temperature shifts, intense rainfall in the catchment area, very rapid changes in turbidity and colour, and seasonal changes in raw water chemistry and organic content. These changes can influence the treatment process and therefore the coagulation conditions. These changes should be reflected in the jar testing. With experience, the operators can learn how raw water quality changes influence in the process.

Low temperatures can have a negative effect on chemical dispersion and reaction rates; under normal conditions this influence is minimal. Without adjustment of pH, floc formation can be very slow at low temperatures. The optimum pH for coagulation shifts to a higher value at low temperatures. At 25°C, aluminium is least soluble at a pH near 6. At 4°C, aluminium is least soluble at pH 6.5-7 (Bache and Gregory 2017). If water is treated at pH 6 throughout the year, levels of aluminium residual will be higher in winter. Aluminium residual after filtration can cause flocs to form in the distribution system, which can lead to dirty water and customer complaints. Temperature changes cannot have a measurable effect on the floc formation time if coagulation occurs at the optimum pH or optimal coagulant is used.

The efficiency of C-F can also be affected by the raw water turbidity. At very low turbidity, particles or colloids interact with little contact opportunity. Therefore, a high coagulant dose is required. As particles increase, less coagulant should be needed as there will be more contact opportunities between coagulant and colloids. Raw water alkalinity and pH are also critical factors in C-F. If the raw water does not have enough alkalinity, the pH can become too low for effective coagulation and alkalinity needs to be added prior the addition of metal coagulant (Murray and Moss 2015). Coagulant conditions must be optimised based on raw water quality. Table 1 shows the recommended jar testing condition to test for different raw water quality.

Table 1: ***Water quality for coagulation issues versus recommended jar testing actions***

Raw water quality parameter	**Range**	**Problem**	**Recommended coagulation conditions**
Alkalinity	Low (<20 mg/L $CaCO_3$)	Sufficient alkalinity is not present; soluble alum is formed, which can result in post flocculation in downstream processes	Increase alkalinity (e.g. soda ash or lime)
	High (<100 mg/L $CaCO_3$)	High alkalinity values make pH adjustment for optimum coagulation more difficult	Increase acid dose

Raw water quality parameter	Range	Problem	Recommended coagulation conditions
True colour	High (>25 HU)	High turbidity in water can occur, high coagulant dose can be consumed	Reduce pH to between 5.5 and 6.2. Increase alum dose, add polymer as a secondary coagulant
Natural organic matter (NOM)	High (humic acids presence)	The removal of NOM controls the coagulant dose	Removal of NOM tends to increase as pH is reduced. Reduce pH to between 5.5 and 6.2
Raw water pH	Low (<5.5)	The optimum pH range is between 6 and 7 and will fluctuate seasonally. Typically, pH will be nearer to 6 in the summer and 7 in the colder winter months	Increase alkali dose Decrease acid dose
	High (>7.0)	Higher pH levels correspond to periods of algal growth, which affect the coagulant dose	Increase acid dose Reduce alkali dose
Temperature	Low (<4° C)	Alum is least soluble at low water temperature. Floc formed tends to be weaker, floc formation can be very slow	Altering pH, higher coagulant doses or add flocculant aid. Typically, pH will be nearer to 6 in the summer and 7 in the colder winter months. Longer flocculation time as reaction time is slower
	High (>25° C)	Alum is very soluble and can result in post-flocculation in downstream processes	Adjust pH to 6.0
Turbidity	Low (<3 NTU) a	NOM removal can be negatively impacted	Increase pH to 7 to produce dense flocs (sweep flocculation), and increase alum dose.
	High (>8 NTU)	Higher residual turbidity in treated water	Reduce alum dose and adjust pH to 6 - 6.5

Source: Bache and Gregory (2017)

The raw water sample should represent the plant's current raw water quality. If a WTP raw water tap is used for sampling, you should ensure that it has been running for at least one hour. Rinse the raw water container with raw water before taking the sample. Collect a minimum 10 L from the raw water sample point. As a minimum measure and record at the pH, turbidity, and true colour of the raw water sample before commencing the jar test.

Fill the 1 L jars with 1000 mL of raw water sample and place under the jar testing stirrers. Lower the paddles into the beaker and stir the sample at approximately 20-30 rpm.

STEP 3: PREPARE THE JAR TESTING EQUIPMENT

The list of equipment recommended for jar testing is summarised in Table 2.

Table 2: ***Recommended jar testing equipment***

Item	Description/ comment
Six jar system with programmed adjustable mixing paddles	
6 x 1000 mL glass circular jars	Ensure jar can hold 1 L. Label each jar 1 to 6
1 x 1 L plastic measuring cylinder	

Item	Description/ comment
1, 2.5, 5, 10 and 20-mL plastic syringes (min 6 syringes of each volume)	Syringes can be reused for chemical dosing, and rinse with deionised water after usage. Use the same syringe for the same chemical
Whatman No.1 filter paper circles	Required if WTP has a filtration process after C-F
6 x 500 mL plastic Erlenmeyer flasks	Required if WTP has a filtration process after C-F
6 x medium plastic funnels	Required if WTP has a filtration process after C-F
Stock solution(s) of the chemicals to be tested	
7 x 50 mL plastic beaker	Label each beaker 1 to 6 and RW (raw water beaker)
1 x jar testing recording sheet	
1 x 20 L plastic drum with lid	Raw water collection
2 x 500 mL volumetric flask	Required to prepare the stock solutions

STEP 4: PREPARE DILUTED SAMPLES OF THE COAGULANT AGENT

A new coagulant solution should be made up whenever a new batch or chemical is received and/or renewed, as indicated by the shelf life. Table 3 shows the strength and shelf life of typical coagulants used in Australia.

The floc properties of the coagulants used in jar testing are summarised in Table 3. Inappropriate floc properties may lead to inefficient downstream separation and problems, including filter blockage, poor algal cell recovery, toxin release and disinfection by-product production.

Table 3: ***Typical jar testing agent solutions for jar testing***

Flocculating agent	Typical stock solution strength	Shelf life	Details
ACH (aluminium chlorohydrate)	23% Al_2O_3 SG 1.33	2 months	Not affected by raw water alkalinity and temperature, produce strong and rapid flocs
Alum	24% Al_2O_3 1% w/v =10 g/L of supplied liquid SG 1.3	1 month	Affected by raw water temperature, alkalinity and pH. Small and dense flocs are formed at pH 6-7
Ferric chloride	15% w/v =10 g/L of supplied liquid SG 1.45	1 month	Large and strong flocs and work in a wider pH than alum
Polyaluminium chloride (PACl)	20-23% w/w SG 1.18	1 month	Dense flocs, less affected by temperature
Cationic polyDADMAC	0.1%w/v=0.1 g/L of supplied polyacrylamide	2 weeks	Reduce of alum dosages, sludge production and alkalinity consumption improved metal ion coagulation turbidity and colour removal
Non-ionic/anionic polyacrylamide	0.01% w/v=0.1 g/L of supplied polyacrylamide	1 week	Flocculant aid, filter aid, filter conditioning. Filter aid doses are not generally determined by jar testing.

Source: Murray and Mosse (2015)

The series of jar test should be performed by optimising the dose of one coagulant at a time. The approach that we recommended is described in Table 4.

Table 4: ***Coagulant testing approach***

Action	Detail
Optimise coagulant dose (primary coagulant)	One coagulant at a time
Define optimal pH	Optimise alkali/acid dose
Optimise polymer (secondary coagulant)	Optimise dose with the coagulant and pH adjusted if it is required
Optimise flocculant aid	Optimise with the optimised primary coagulant and alkali/acid dose

The coagulant dose should be adjusted according to the objective of the jar testing. Table 5 shows an example of typical coagulant dose to test based on the jar testing objectives. Fill syringes with the required volume of stock solution for each jar. Set in the correct order in the jar tester.

Table 5: ***Typical coagulant solutions for jar testing***

	Coagulant dose as mg/L					
Jar test objective	**Jar 1**	**Jar 2**	**Jar 3 (current dose)**	**Jar 4**	**Jar 5**	**Jar 6**
Fine tuning	31	33	35[a]	37	39	41
Diminished raw water quality	30	35 [a]	40	45	50	55
Unknown water quality	10	20	30	40	50	60

Source: Murray and Mosse (2015)

STEP 5: DETERMINE MIXING CONDITIONS

The jar testing should be set up to simulate the plant operating conditions. Similar initial mixing and flocculation energies (G) and contact times should be used. For example, if the plant has a flash mix system, the G of the system can be used to determine the mixing speed in jar testing using a relationship specific to the jar tester which should be request to the jar testing supplier. Table 6 shows the recommendation of jar testing set-up and desired floc properties depending of the separation process.

Table 6: ***Jar testing set-up and mixing conditions guidelines***

Separation process	Mixing stage			Optimal floc properties
	Rapid	**Slow**	**Detention**	
Contact filtration/ direct filtration	Time: 30-60 sec (or the same mixing time as in the WTP) rpm: maximum rpm if actual design G is unknown	Time: same contact time as in the WTP/ same as the WTP flocculation time rpm: approx. 30-35 rpm/ 50 rpm if actual design G is unknown	Time: 1-5 min/ 5-20 min rpm: 0	Medium and strong flocs to avoid floc rupture during filtration
Dissolved air flotation	Time: 30-60 sec (or the same mixing time as in the WTP) rpm: Maximum rpm if actual design G is unknown	Time: same contact time as in the WTP rpm: 30-35 rpm if actual design G is unknown	None	Small and strong flocs desirable to avoid floc rupture due the turbulent regime introduced via the release of air saturated recycled water through nozzles or valves
Sedimentation	Time: 30-60 sec (or the same mixing time as in the WTP) rpm: Maximum rpm if actual design G is unknown	Time: same contact time as in the WTP rpm: 30 rpm if actual design G is unknown	Time: 30 min to settle rpm: 0	Large and dense flocs are desirable to overcome the low density between floc particle and water

Source: Gonzalez, Torres et al. (2014)

STEP 6: ADD FLOCCULATING SOLUTION TO RAW WATER
When using hydraulic coagulants (e.g. alum), the most reasonable chemical application sequence is first to lower the raw water's pH by adding alum or acid to form more highly charged species. Dose polymer at the same time as a metal coagulant. The next step is to adjust pH of the water to the range for minimum aluminium or iron solubility to facilitate floc formation. If pH and alkali deficiency need to be corrected, lime and caustic soda can be more effective if they are fed at least several seconds after the metal coagulant feed. When lime is added immediately after coagulation, it was found that floc settlement improved (Bache and Gregory 2017).

STEP 7: RECORD JAR TEST DATA AND RESULTS
Measure and record turbidity, true colour, pH for each jar after the test has been ended. Aluminium, iron and alkalinity can also be measured. Keep a soft and hard/ copy of the jar testing laboratory results, aim of the test and stock solutions details.

STEP 8: ANALYSIS RESULTS

Determine and record the best jar test based on the laboratory results and observations, which has the lowest turbidity and true colour. If the water does not have enough coagulant, the water is similar to raw water, cloudy with little or no floc (Murray and Mosse 2015). If the water has overdosed, dense and fragile flocs are formed which cannot settle well. Repeat the above steps with different doses if necessary to narrow down the optimum dose for each chemical or at different pH to determine the optimal pH. Trial the best dose in the plant.

3. CONCLUSION

A basic and empirical guide for jar testing was designed to reduce some of the constraints of jar testing. This guide can be tailored to reflect performance of a water treatment plant accurately. The link between the physical floc properties, coagulant and separation units were described to provide some tools for the selection of jar testing conditions, to aid process optimisation and give information that is likely to impact the downstream separation.

4. REFERENCES

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