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Historical perspective

A comprehensive review on rheological studies of sludge from various sections of municipal wastewater treatment plants for enhancement of process performance

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ABSTRACT

Large quantities of sludge is generated from different sections of a wastewater treatment plant operation. Sludge can be a solid, semisolid or liquid muddy residual material. Understanding the flow behaviour and rheological properties of sewage sludge at different sections of a wastewater treatment plant (WWTP) is important for the design of pumping system, mixing, hydrodynamics and mass transfer rates of various sludge treatment units, optimization of conditioning dose and for sustainable sludge management. The current article provides a comprehensive review on up to date literature information on rheological behaviour of raw primary sludge, excess activated sludge, thickened excess activated sludge, mixture of raw primary and thickened excess activated sludge (mixed sludge), digested sludge, and biosolid under the influence of different operating parameters and their impacts on process performance. The influences of various process parameters such as solid concentration, temperature, pH, floc particle size, primary to secondary sludge mixing ratio, aging and conditioning agent doses on the rheological behaviour of sludge from different treatment units of WWTPs are critically analysed here. Yield stress was reported to increase with increasing solid concentration for all types of sludge whereas viscosity showed a decreasing trend with decreasing total solid concentration and percentage of thickened excess activated sludge in the mixture. Temperature showed an inverse relationship with yield stress and viscosity. Viscosity was reported to be decreased with decrease in pH. The effect of various conditioning agents on the rheological behaviour of sludge are also discussed here. The applicability and practical significance of various rheological models such as Bingham, Power Law (Ostwald), Herschel-Bulkley, Casson, Sisko, Careau, and Cross models to experimental rheological characteristics of various sludges were presented here. The reported results on various rheological parameters such as shear stress, yield stress, flow index, infinite, zero-rate viscosity, and flow consistency index of different sludge types obtained from the best fitted model were also compiled here. Conclusions have been drawn from the literature reviewed and few suggestions for future research direction are proposed.

Contents

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1. Introduction

Rheology is the study of flow and deformation of materials under applied forces. The rheology of Non-newtonian fluids like, polymers, detergents, pastes and wax, oil and biological materials like sludge is very complex and requires thorough investigation [1–7]. This particular research reviews the rheological flow behaviour of municipal sewage sludge. Published articles in recent years have reported different aspects of the rheological flow behaviour of sludge from different parts of municipal wastewater treatment process. Sustainable sludge and wastewater management is getting increasingly more difficult with the rapid growth of urban population and the demand for environmentally friendly methods for disposal. This in turn demands the development of present technologies and operation for wastewater treatment plants such as improving pumping, hydrodynamics, mass transfer rates, sludge settling, filtration and other related processes. Significant improvement in monitoring, control and performance of wastewater treatment processes can be achieved by investigating flow and rheological behaviour of sludge. A larger number of research work has been conducted in the area of sludge rheology [5–14]. The rheological flow behaviour is highly influenced by wastewater treatment operating parameters such as source of sewage, total solid concentration of sludge, temperature, and sludge treatment methods [5–7, 9, 13, 15]. Studies show that sludge is highly complex in nature and needs detailed investigation to improve the understanding on the impacts of different operating parameters on the rheological and flow properties of different sludge type [5–7, 13]. A typical wastewater treatment plant generally consists of four stages, which are preliminary, primary, secondary, and advanced treatment stages. Different types of sludge are generated from these various treatment sections, such as raw primary sludge, excess activated sludge, and thickened excess activated sludge, mixed sludge, digested sludge and biosolid. Raw primary sludge that comes from the underflow stream of primary sedimentation tanks is transferred to secondary treatment units of aeration and sedimentation where nutrient removal and biomass accumulations takes place [16]. The product of the secondary treatment process, activated sludge, is thickened in the dissolved air flotation thickener (DAFT) to form thickened excess activated sludge. Thickened excess activated sludge is a complicated colloidal material which is composed of organic and inorganic particles. Raw primary sludge and thickened excess activated sludge is then mixed to form mixed sludge which is fed to the anaerobic digesters for further degradation [17]. The product of the anaerobic digestion process, digested sludge, would be fed to the dewatering plant for further solid-liquid separation. Both the anaerobic digestion and sludge dewatering operations account for approximately 70% of the overall wastewater treatment plant operation cost, making it a vital process for rheological investigation [9, 13, 15, 16, 18].

Sludge rheology (viscosity, yield stress and shearing behaviour) is affected by many factors including total solid concentration, temperature, pH, dose of polymer or other agents, chemical composition especially concentration of biopolymers and organics [5–7, 11–14]. According to Einstein law of viscosity, solids existing within a fluid is considered as a key factor that contributes to non-Newtonian flow behaviour [19]. Different sludge types generally behave like a non-Newtonian and shear thinning material, which has been reported in many literature [11, 19–24]. Total solid content is a parameter that influences the rheological and flow behaviour of sludge types. It was found that increasing viscosity of sludge due to the increase of solid content will lead to stronger inter-particle interactions which are caused by the size increase of particles in suspension, resulting in higher apparent viscosity for different sludge types [5–7]. Experimental studies have confirmed that solid content is a key parameter that highly influences the rheological behaviour. It helps to validate the dynamic and complex nature of different sludge types. Baudez [25] also found that shear stress and shear rate increase with the increase of total solid content and are highly dependent on the fractal dimensions of the floc. Utilizing one parameter alone such as total solid content to describe the rheological behaviour is not adequate hence the use of multiple parameters is recommended to improve the understanding [5–8, 26, 27]. Temperature is one of those key parameter that has strong effect on the rheological properties by affecting flocculated particle size, shape, and degree of dispersion within the different sludge types [19]. Studies have shown that yield stress increases with increasing total solid content but decreases with increasing temperature, while viscosity shows lower values at higher temperature [5–7, 11, 28–30]. pH is another parameter which highly influences the rheological behaviour of different sludge types. The network strength and surface charge of particles change as the pH is increased or decreased [31, 32]. Studies on the relationship between rheological characteristics of digested sludge and dewatering performance particularly on rheology as an indicator or monitoring tool of dewatering performance are only emerging very recently.

According to Hong, Yeneneh [5], Yeneneh, Hong [6], Hong, Yeneneh [7], Markis, Hii [18], Hong, Yeneneh [27], studies on different sludge types are few, limited, and inconsistent. Furthermore, literature agrees that each type of sludge is unique to the source, hence different sludge types have different rheological properties; therefore, future research should continue to improve overall understanding on the various aspects of sludge rheology [10, 18, 33, 34]. Furthermore, the effect of rheological behaviour of sludge from different parts of wastewater treatment plant on pumping cost, mixing and mass transfer are very scattered and limited. Therefore, this review article first time presented the up to date literature information on rheological behaviour of raw primary sludge, excess activated sludge, thickened excess activated sludge, mixture of raw primary and thickened excess activated sludge (mixed sludge), digested sludge, and biosolid under the influence of different operating parameters and their impacts on process performance of a wastewater treatment plant (WWTP). This review paper intends to show the findings of published literature on the rheological characteristics of sludge coming from different parts of wastewater treatment plant under the influence of key operating parameters. Rheological measurement techniques and standards for sludge systems have also been included in this review. The challenges and the research gaps were addressed accordingly.

2. Rheological modelling of sludge

According to Björn, Karlsson [35], ideal fluids exhibits rheological behaviour, which is linear and are classified as Newtonian fluids, while non-Newtonian fluids exhibit a non-linear rheological behaviour

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