

RHEOLOGICAL PROPERTIES AND OPTIMIZATION FOR DIFFERENT TYPES OF CONCRETE: A REVIEW

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ABSTRACT

Controlling concrete's rheology is so important these days, especially for various types of concrete to avoid concrete problems during the pouring process, such as segregation, bleeding, and poor consolidation. The primary objective of this research is to optimize the rheological properties of various types of concrete. A comparison of rheological properties for cement pastes, mortar, and concrete will be discussed in this review. Different types of tests to determine rheological properties (e.g., yield stress, plastic viscosity, or both at the same time) for concrete by either one-factor tests or two-factor tests. Factors impacting the rheological properties of concrete, including mix proportions of concrete ingredients, shapes, size, and texture of aggregates, grading of aggregates, and various types of admixtures, would be illustrated in more detail. The optimization of concrete and mortar rheology would be elaborated for high-performance concrete, traditional concrete, self-compacting concrete, and geopolymer mortar.

KEYWORDS: Self-Compacting Concrete, High-Performance Concrete, Concrete Rheology, Yield Stress, Plastic Viscosity, Geopolymer Mortar.

1. INTRODUCTION

Kosmatka and Panarese [1] defined the following three terms when referring to concrete rheology, including workability, consistency, and plasticity. The Bingham model is a linear approximation of a material or fluid's shear stress-shear rate relationship, as shown in Fig.1 [2], which is described by two material parameters: yield stress and plastic viscosity. The Bingham yield stress of concrete is related to slump [3]. Many new methods have recently been developed to measure yield stress and plastic viscosity, as shown in Fig.1. The viscosity definition is the resistance of a fluid to flow after movement is started. The higher the viscosity, the higher the material's resistance to flow. Plastic viscosity is the slope of the approximate red line, as shown in Fig.1. The relationships for fluids can be described by plotting shear stress versus the shear rate [4, 5]. Yield stress is the stress required to initiate material flow. Typically, two types of yield stresses can be considered:

- Static yield stress is the stress needed to transition from a solid to a liquid state. As most cementitious materials exhibit thixotropy, the static yield stress increases over time [6, 7].
- Dynamic yield stress is the apparent stress where the material transitions from liquid to solid behavior.

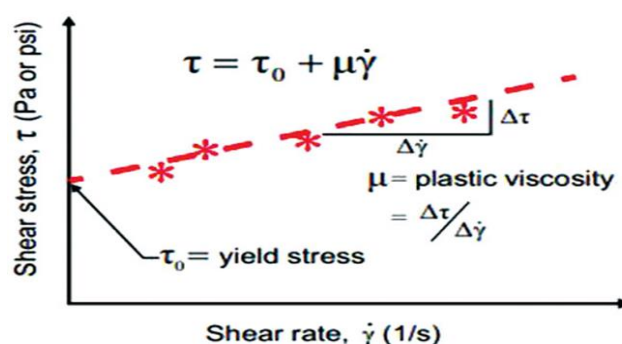


Fig. 1. The Bingham model of concrete; red stars represent experimental data points approximated using a straight line.

Table 1 shows the equations used for concrete rheology, incorporating the yield stress and the plastic viscosity parameters. The Bingham equation is the common equation utilized in the description of the flow behavior of the cement matrix, as shown in equation 1.

$$\tau = \tau_0 + \mu_{pl} \cdot \gamma \quad [1]$$

where: τ : shear stress (Pa), τ_0 : yield stress of the cement paste (Pa), μ_{pl} : plastic viscosity of the cement paste (Pa·s), γ : shear rate (s⁻¹).

Table 1. Equations relating shear stress and shear rate

Equations	Name of Equation
$\tau = \eta \gamma$	Newtonian [8]
$\tau = \tau_0 + \eta \gamma$	Bingham [9]
$\tau = \tau_0 + K \gamma^n$	Herschel and Bulkley [10]
$\tau = A \gamma^n$ where: n = 1 Newtonian flow n > 1 shear thickening n < 1 shear thinning	Power equation [10]

where: τ : Shear stress=F/A, η : Viscosity, τ_0 : Yield stress, γ : Shear rate, A and K: constants, F: shear force, A: Cross-section area of the plane parallel to the force.

1.1. Comparison of rheological properties for cement pastes, mortar, and concrete

Table 2 shows the rheological properties of various types of concrete. The interfaces between solid and water govern the flow properties of suspensions according to Tattersall and Banfill [11]. The two main parameters for concrete rheology increase as the maximum particle size of the aggregates increases. The yield stress for typical concrete is higher due to the presence of aggregate content in the concrete matrix. Moreover, the increased plastic viscosity is due to the increased interparticle contact and surface interlocking.

Table 2. Rheology of cement paste, mortar, and concrete, adapted from Tattersall and Banfill [11].

Types of Concrete Parameters	Cement Paste	Mortar	Flowable Concrete	Self-Compacting Concrete	Concrete
Yield Stress (N/m ²)	10-100	80-400	400	50-200	500-2000
Plastic viscosity (N.s/m ²)	0.01-1	1-3	20	20-100	50-100
Structural breakdown	Significant	Slight	None	None	None

A structural model for shear-induced breakdown in cement systems is shown in Fig. 2 [12, 13]. For example, when dry cement powder first encounters water, the hydrated skin or membrane may form around groups of particles. This model is consistent with the formation of a protective layer on cement and the links between particles, according to Tattersall and Banfill [11].

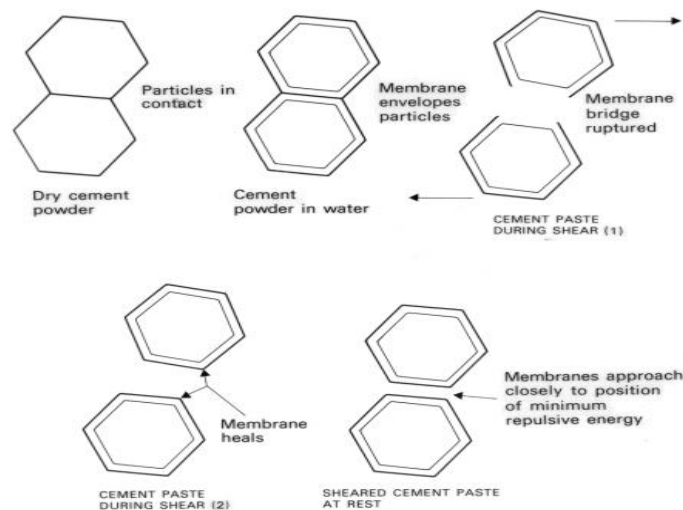


Fig. 2. Structural model for shear-induced breakdown in cement systems [11-13]

2. TEST METHODS FOR CONCRETE RHEOLOGY

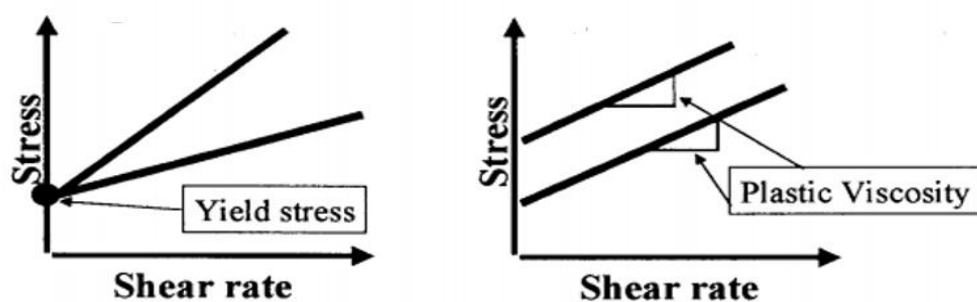
Test methods for the flow properties of concrete can be divided into two groups, depending on whether the experiment's output gives one or two parameters (e.g., yield stress and plastic viscosity) that need to be measured.

2.1. One-Factor Tests

Different one-factor tests to measure only one rheological factor, whether yield stress or plastic viscosity, are illustrated in Table 3.

Table 3. One-factor test for concrete rheology.

Type of Tests	Measurement Types
Slump Test [2, 14] The main disadvantage of this type of test is that if two fresh concrete mixtures have the same slump it may behave differently in rheological properties (see Fig. 3).	Yield Stress
Penetrating rod: Kelly ball, Vicat, Wigmore test. These tests compare whether the applied stress is higher or lower than the yield stress of the concrete.	
K-slump Test	
Ve-Be Time or Remolding Test LCL Apparatus The time for the concrete to flow and occupy the whole prism is considered a measure of workability according to De Larrard [15].	Plastic Viscosity
Vibration Testing Apparatus or settling curve	
Turning tube viscometer	
Filling ability [15, 16]	
Cons: If the stress applied is lower than the yield stress, no measurement will be obtained.	
Orimet Apparatus	Measures both plastic viscosity and yield stress.
Flow cone	



(a) Same yield stress but different viscosity (b) Same plastic viscosity but different yield stress

Fig. 3. Disadvantages of the slump test for two concrete mixes with the same slump.

2.2 Two-Factor Tests

2.2.1 Rotational Rheometers (Dynamic Tests)

Rheometers apply shear to concrete specimens through rotational movement at various types of rheometers (see Fig.4). For different types of rotational rheometers, the rheological parameters can be deduced from the measured torque and speed. The parallel plate rheometers are utilized in the cement paste only.

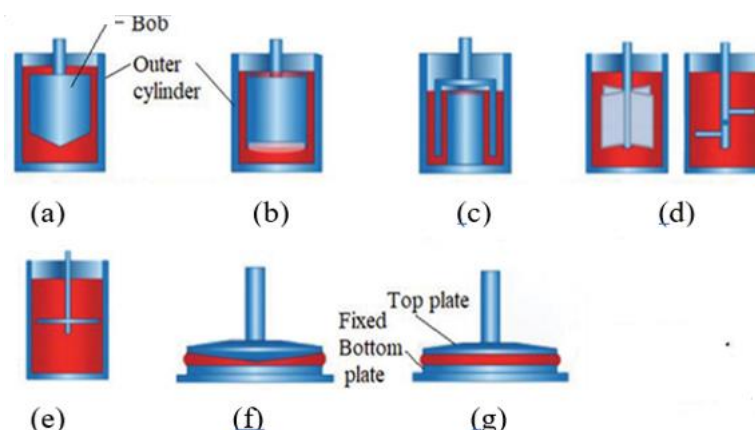


Fig. 4. Different types of rotational rheometers adapted from Küchenmeister- Lehrheuer and Meyer [17]; the red color represents the fluid to be tested. (a) Coaxial cylinders, (b) Coaxial cylinders with recessed bottom, (c) Double gap geometry, (d) Vane and Helical impeller, (e) ISO 2555, (f) Cone and plate, (g) Parallel plates

The basic principle for rotational rheometers is to measure the relationship between torque (T) and rotational speed (N); the slope (h) of the inclined line and the intercept (g) of the torque axis after linear regression can then be deduced, as shown in equation 2. According to the theoretical model of the rheometer, as described by Tattersall and Banfill, the rheology of concrete can be simulated using the Bingham model, as shown in equation 3, for which a shear stress (τ) exists before the initiation of flow. Equation 2 can be converted to represent the relationship between shear stress and shear strain rate, as shown in Fig. 5. Therefore, the plastic viscosity and yield stress can be calculated using equation 3 [18].

$$T = h \times N + g \quad [2]$$

$$\tau = \tau_0 + \eta \dot{\gamma} \quad [3]$$

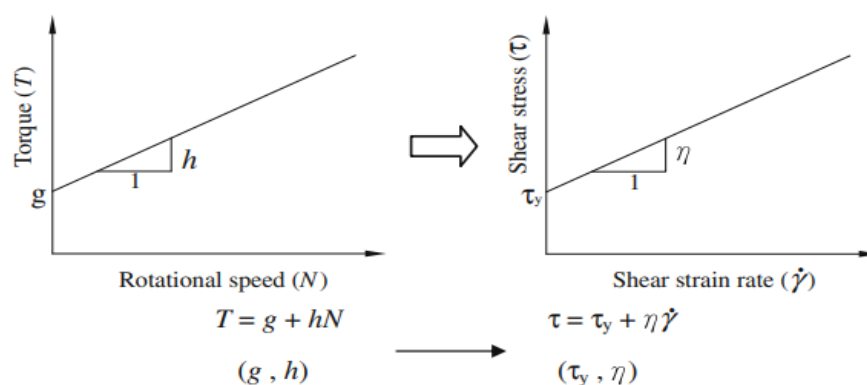


Fig. 5. Bingham model transform adapted from Jau and Yang [18].

2.2.2. Tattersall Two-Point Test

Tattersall developed the first two-point rheometer in 1973. The different pieces of Tattersall's two-point equipment have embedded software built into them, automatically converting the applied torque and speed to yield stress and plastic viscosity. Equation 4 shows that the effective average shear rate is proportional to the speed of the impeller, according to Tattersall's equation.

$$T = (G/K) \tau_0 + (G \eta) N \quad [4]$$

where: T: torque, G: constant obtained by calibration with Newtonian fluids, K = constant obtained by calibration with non-Newtonian fluids, N: speed of the impeller, τ_0 : yield stress, and η = viscosity.

Therefore, $\tau_0 = g/(G/K)$ and $\eta = h/G$, where g and h are the two values measured.

2.2.2. BTRHEOM Rheometer

The shear stress distribution allows direct viscosity and yield stress calculation according to the following equations 5 and 6, based on the assumption of a Bingham fluid.

$$\tau_0 = \frac{3 r_0}{2\pi(R_2^3 - R_1^3)} \quad [5]$$

$$\eta = \frac{2h(\frac{dr}{d\Omega})}{\pi(R_2^3 - R_1^3)} \quad [6]$$

where: τ_0 : shear yield stress; η : viscosity; R_1 and R_2 : inside and outside radii of the apparatus; h: height of the sheared part of the sample; r: torque applied to the sample; Ω : angular velocity of the rotating part; r_0 and $dr/d\Omega$: ordinate at the origin and slope of the experimental straight line $r(\Omega)$.

2.2.3. Modified Slump Cone Test

The slump cone was modified from the original slump test to measure the viscosity. The modification measures the final slump height and the speed at which the concrete slumped. There are two methods to measure the speed at which the concrete slumped [2], as shown in Fig. 6.

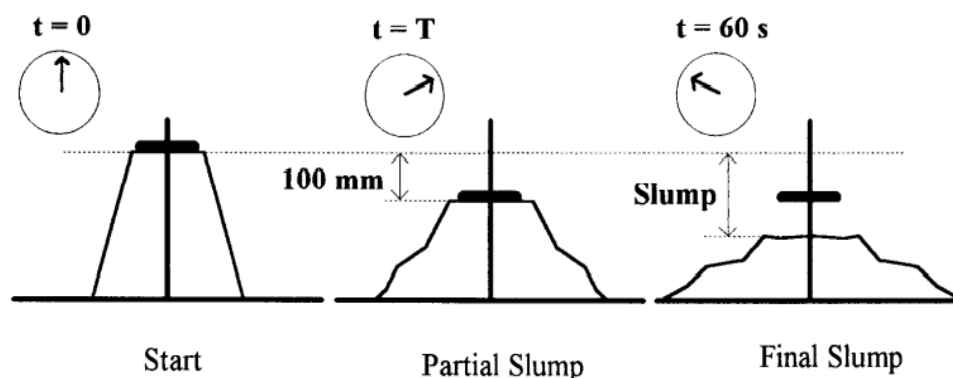


Fig. 6. Schematics of the modified slump cone test adapted from Ferraris and De Larrard [2].

The yield stress (τ_0) can be calculated using the following empirical equation 7.

$$\tau_0 = (\rho/347) (300 - S) + 212 \quad [7]$$

Where ρ is the density expressed in kg/m^3 , and S is the final slump in mm.

Viscosity is calculated from the 100 mm slump time using an empirical equation that was defined by de Larrard et al. [19] according to the final slump value.

$$\mu = \rho T \times 1.08 \times 10^{-3} (S-175) \quad \text{for } 200 \text{ mm} < S < 260 \text{ mm} \quad [8]$$

$$\mu = 25 \times 10^{-3} \rho T \quad \text{for } S < 200 \text{ mm} \quad [9]$$

Where: μ is the viscosity (Pa.s), and T is the slumping time in seconds.

3. FACTORS AFFECTING THE RHEOLOGICAL PROPERTIES OF CONCRETE

Rheological properties of fresh concrete depend upon the mixed proportions of ingredients, the properties of ingredients, the types of admixtures, the amount of mixing, and the time elapsed after the rheology of concrete. The factors that affect concrete rheology, based on Wallevik and Wallevik [20], are shown in Table 4 [21, 22].

Table 4. Factors affecting concrete rheology properties

Factors	Concrete Rheology
Mix Proportions of Constituents	- As the amount of coarse aggregate increases in the concrete mix, it will result in a loss of cohesion. - The number of fine aggregates increases, which will increase cohesion and result in difficult concrete movement [14]. - The amount of cement increases, which will result in sticky concrete. It also reduces the workability of concrete.
Consistency of Concrete	- The amount of water content in the mix that is more than required will not enhance the concrete rheology properties. - While the water content is less than the required amount will reduce mobility and compatibility, which will cause difficulties in placing concrete.
Shapes, Size, and Texture of Aggregates	- The rough and angular aggregates need a higher amount of water content. - In the same way, angular fine aggregates will require higher water content than natural sand [14].
Grading of Aggregates	- A well-graded aggregate results in good workability. - Variations in the aggregate size will impact the workability. - If coarse aggregates increase, the concrete mix becomes harsh, and bleeding will increase [14].
Types of Admixtures	- Superplasticizers are synthetic sulfonated melamine or naphthalene-formaldehyde polymers, which can be added at sufficient concentrations to reduce the yield stress of cement paste to zero without causing excessive retardation. There is a correlation between the amount adsorbed and the reduction in yield stress [23, 24]. - Plasticizers and superplasticizers are the admixtures that affect the rheology of concrete. - The impact of the superplasticizer on the yield stress of concrete would be reduced to very low values by the dispersion of lumpy cement particles [11, 25].

Based on experimental data conducted by Flatt and Houst [26], three components of the behavior of the superplasticizer added to the cement system matrix were proposed. The first part is consumed by intercalation within the hydrating cement minerals, forming an organo-mineral phase. The second part is available for adsorption at the surface of cement particles and is effective in dispersing the flocs, but



the adsorbed amount is not easily measured. The third part consists of dissolving the superplasticizer in the aqueous phase and playing a part in dispersing cement particles.

4. OPTIMIZATION FOR CONCRETE RHEOLOGY

The optimization of concrete rheology will be discussed in this section for various types of concrete rheology, including high-performance concrete, traditional concrete, self-compacting concrete, and geopolymer mortar.

4.1. Optimization for High-Performance Concrete (HPC)

The paste's yield stress and plastic viscosity increase as the water-to-cement ratio (w/c) decreases and the cement becomes finer. These properties are further modified (up or down) by incorporating SCMs. The existence of aggregate in the concrete mix would lead to a higher yield stress of concrete than that of the cement paste. Aggregate angularity, surface texture, maximum particle size, gradation, packing, and content can significantly affect concrete viscosity and yield stress. Admixtures such as viscosity-modifying agents (VMAs) and water-reducing admixtures (WRAs), normal and high-range, can enhance placement, consolidation, and finishability of concrete and even increase thixotropy without the need to adjust the water content. Increasing water content can decrease both the yield stress and plastic viscosity. The use of a higher amount of silica fume as a partial replacement for cement content in the concrete mix can increase the yield stress and plastic viscosity (see Fig. 7) [27].

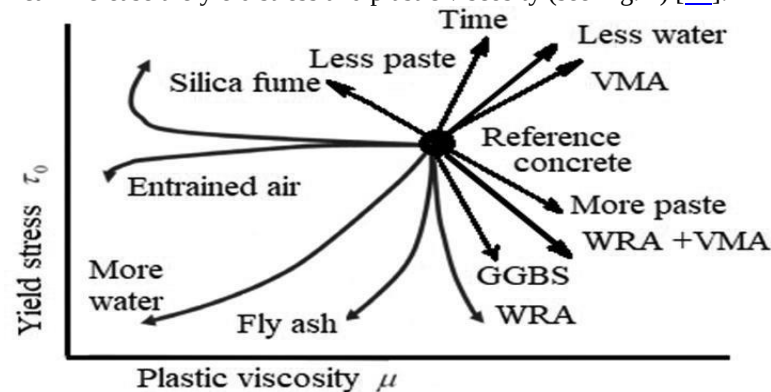


Fig. 7. Effect of ingredient materials on the rheological properties of HPC, adapted from Banfill [12].

Table 5 shows the impacts of various concrete ingredients on the rheological properties of high-performance concrete. All components of the mixture for the high-performance concrete, such as cement content, water-cementitious materials ratio, supplementary cementitious materials (SCM), chemical admixture amount, and types of aggregate and content, and gradation, play an important role in high-performance concrete rheological properties (see Table 5).

Table 5. Parameters influencing HPC Rheology [14].

Table 3: Parameters Influencing HPC Performance [24].		
Parameter	Yield Stress	Plastic Viscosity
Increase in Cement Content	Decrease	
Increase in Water Content	Decrease	
Aggregates		
Volume Fraction	Increase	
Shape	Rounded aggregates perform better than angular and elongated aggregates.	
Texture	Smooth is better than rough	
Gradation	Uniform gradation and high packing density perform better.	
Micro-fine Content	Mixed	
Sand to Aggregate Ratio	Optimum Value	
Supplementary Cementitious Materials		

Fly Ash	Decrease	Mixed
GGBFS	Mixed	Increase
Silica Fume (Low Dosage)	Decrease	
Silica Fume (High Dosage)	Increase	
Admixtures		
Water Reducing	Decrease	Mixed
Air entraining	Mixed	Decrease
Viscosity Modifying	Increase	
Fiber Content	Increase	

4.2. Optimization for traditional concrete

To achieve better quality for traditional concrete by limiting segregation, producing a good surface finish, and minimizing pumping pressure, it is necessary to balance the rheological properties of traditional concrete. Ferraris et al. [28] and Ferraris and Brower [29] suggested the following:

1. Control segregation by increasing the yield stress or plastic viscosity, considering that increasing both parameters excessively will lead to very stiff concrete.
2. Achieve a good surface finish by having adequate plastic viscosity.
3. Decrease pumping pressure by decreasing plastic viscosity.
4. Reduce formwork pressure.

4.3. Optimization for self-compacting concrete

The rheology of self-compacting concrete will likely differ depending on the adopted solution. It can be noted that a low yield stress and a low plastic viscosity together are not a satisfactory combination; this gives segregation [30]. A low-yield stress concrete must have a high plastic viscosity, but there are upper limits to the acceptable values of both parameters. Otherwise, the concrete is not self-compacting [31-34].

The difficulty with a low yield stress is that concrete is prone to segregation, with the fine matrix filtering through the coarse particles, and it is necessary to thicken the fine matrix. Various methods to overcome segregation are as follows:

- (i) Utilizing high powder contents.
- (ii) Water-soluble thickeners.
- (iii) Entrained air bubbles.

4.4. Optimization for geopolymer mortar

Rheological properties, including yield stress and plastic viscosity, and correlation between yield stress and plastic viscosity of sustainable construction and demolition wastes-based geopolymer mortars that included recycled clay brick, recycled ceramic tile, and recycled concrete as demolition wastes-based precursors along with MK as SCM, as well as the effects of aggregate types, were extensively investigated. Recycled concrete aggregate, silica sand, and natural sand were utilized as fine aggregates. The following main conclusion points were observed based on the experimental data conducted by Mahmoodi et al. [35]:

- Geopolymer mortars' shear stress, viscosity, and yield stress improved as the recycled ceramic tile particles were incorporated and increased in recycled concrete binders.
- The addition of recycled clay brick into recycled concrete binders also caused increased rheological parameters, with a reduced effect compared to recycled ceramic tile.
- The effect of various types of fine aggregates in the mix has a significant impact on the rheological properties of geopolymer mortars. The use of silica sand showed improved flow tendency and shear strains, instantaneously producing lower stresses and viscosities than natural sand-based geopolymer mortars, which showed comparatively higher rheological properties.
- The addition of recycled concrete aggregate in geopolymer mortars diminished flow tendency while enhancing yield stresses, plastic viscosity, and rigidity due to increased inter-particle interaction. However, it produced higher thixotropy, especially at the early stages of geopolymerization.

- The demolition waste-based geopolymer mortars exhibited thixotropic behavior and varied levels of viscosity recovery abilities. Geopolymer mortars comprising recycled ceramic tile binder or recycled concrete aggregate fine aggregates showed higher thixotropy than other geopolymer mortars.
- The type of fine aggregate had a clear impact on the mechanical properties of mortars. With lower yield stress, silica sand compositions exhibited higher compressive strengths than natural sand and recycled concrete aggregate-based geopolymer mortars.
- Using recycled concrete aggregate particles with increased water absorption and porosity caused a significant decline in the compressive strengths of geopolymer mortars.

5. CONCLUSIONS

- Different mathematical models to describe the rheology and flow for various types of concrete are presented based on various literature.
- The Bingham mathematical equation is the most used in the description of the flow behavior of various concrete properties according to Nagaraj and Girish [36], El Bitouri [37], and Liu et al. [38].
- Comparison of rheological properties for cement pastes, mortar, and concrete is discussed concerning yield stress, plastic viscosity, and structural breakdown.
- Test methods for concrete rheology to measure yield stress or plastic viscosity, individually via one-factor tests; However, two-factor tests can measure both yield stress and plastic viscosity at the same time.
- The main con of the slump test (one-factor test) is that if two fresh concrete mixtures have the same slump it may have different rheological properties.
- Factors affecting the rheological properties of concrete, including mixed proportions of concrete ingredients (cement type, water content, etc.), shapes, size, and grading of aggregates, and various types of admixtures, are discussed to observe their effect on concrete rheological properties.
- The optimization of concrete rheology for various types of concrete and mortar, including high-performance concrete (HPC), traditional concrete (TC), self-compacting concrete (SCC), and geopolymer mortar (GPM). The main conclusions are as follows:
 1. In HPC, the increase in water content can decrease both the yield stress and plastic viscosity. Moreover, the use of a higher dosage of silica fume as an SCM in the concrete mix can lead to an increase in the yield stress and plastic viscosity, and vice versa.
 2. A low-yield stress required for self-compacting concrete must have a high plastic viscosity.
 3. For GPM, it was found that the addition of recycled brick made of clay into recycled concrete binders caused increased rheological parameters, with a reduced impact compared to recycled ceramic tile. The type of fine aggregates in the mortar mix has a significant impact on the rheological properties of GPMs.
 4. The use of silica sand showed improved flow tendency and shear strains instantaneously compared to natural sand-based GPMs, which showed higher rheological properties (e.g., yield stress and plastic viscosity).

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