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Effects of incorporating secondary-treated domestic wastewater on the physical properties of concrete.

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ABSTRACT

The objective of this study is to evaluate the feasibility of using secondary-treated domestic wastewater in concrete production and its chemical-mechanical implications. The methodology consisted of a structured literature review focused on chemical composition, hydration, and mechanical properties. The results show high variability: 59% of the cases reported decreased strength, while others showed improvements depending on pH, salts, and dissolved solids. A unique aspect of this study is the integration of chemical-mechanical analysis beyond conventional classifications. The study concludes that its use is viable under controlled conditions, requiring performance-based approaches to ensure durability and sustainability.
Keywords: concrete; secondary-treated domestic wastewater, chemical properties; mechanical properties.

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Contribution of each author
In this work, the author Pedro Israel Silva Martínez contributed with the search and compilation of information, with the analysis of the information in about 50%, the discussion of the results in 50% and the elaboration of the draft of the article. The author Alejandro Meza de Luna contributed with the direction and management of the research, the discussion of the results in 50%, analysis of the information in 50%, as well as the revision and adjustments of the article in 100%, and the functions of corresponding author.

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Efectos de la incorporación de aguas residuales domésticas con tratamiento secundario sobre las propiedades físicas del concreto.

RESUMEN

El objetivo de este estudio es evaluar la viabilidad del uso de aguas residuales domésticas con tratamiento secundario en la producción de concreto y sus implicaciones químico-mecánicas. La metodología consistió en una revisión estructurada de la literatura enfocada en composición química, hidratación y propiedades mecánicas. Los resultados muestran alta variabilidad: 59% de los casos reportan disminución de resistencia, mientras otros presentan mejoras dependiendo de pH, sales y sólidos disueltos. Como originalidad, se integra el análisis químico-mecánico más allá de clasificaciones convencionales. Se concluye que su uso es viable bajo control, requiriendo enfoques basados en desempeño para asegurar durabilidad y sostenibilidad.

Palabras clave: concreto; aguas residuales domésticas tratadas secundariamente, propiedades químicas; propiedades mecánicas.

Efeitos da incorporação de águas residuais domésticas com tratamento secundário sobre as propriedades físicas do concreto.

RESUMO

O objetivo deste estudo é avaliar a viabilidade do uso de águas residuais domésticas submetidas a tratamento secundário na produção de concreto e suas implicações químico-mecânicas. A metodologia consistiu em uma revisão estruturada da literatura, com enfoque na composição química, hidratação e propriedades mecânicas. Os resultados demonstram elevada variabilidade: 59% dos casos relatam redução da resistência, enquanto outros apresentam melhorias, dependendo do pH, da concentração de sais e dos sólidos dissolvidos. Como contribuição original, o estudo integra a análise químico-mecânica para além das classificações convencionais. Conclui-se que seu uso é viável sob condições controladas, sendo necessária a adoção de abordagens baseadas em desempenho para assegurar a durabilidade e a sustentabilidade.

Palavras-chave: concreto; águas residuais domésticas com tratamento secundário; propriedades químicas; propriedades mecânicas.

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1. NOMENCLATURE

BOD_5: Five-day Biochemical Oxygen Demand
COD: Chemical Oxygen Demand
kg/m^3: Kilogram per cubic meter
mg/l: Milligrams per liter
mS/cm: MilliSiemens per centimetre
NO_3^-: Nitrates
NTU: Nephelometric turbidity units
pH: Hydrogen potential
SO_4^{-2}: Sulfates
TDS: Total Dissolved Solids
ppm: Parts per million

2. INTRODUCTION

Water is one of the most critical resources due to its scarcity, representing an excellent challenge for the world's population since drinking water is used not only as a source of human hydration but also as a resource in various industrial fields (Robledo et al., 2017). It is well known that around 75% of the earth's surface is covered with water; however, 3% is consumable for living beings. This percentage is also usable to produce concrete; the construction industry specifies that the liquid used to generate concrete must be in the safest condition to ensure that no chemical or biological reaction occurs that could compromise the physical properties of the final industrial product (Asadollahfardi et al., 2016).

It has been reported that around 100 million tons of potable water are used throughout the earth yearly; this amount is expected to increase due to exponential growth. In addition, in recent years, the human population has demanded more concrete manufacture homes, roads, hospitals, schools, and all facilities necessary to develop human life (Nikookar et al., 2023). To reduce the levels of water consumption in the construction field, different countries propose using different water sources, not necessarily potable or purified, to produce concrete (Yousuf et al., 2023). However, it is essential to consider the presence of undesirable chemical components in the non-potable water that could interfere with the reactions to obtain concrete; for example, dicalcium is related to the cement's hydration reaction and the concrete's final physical properties (Wang et al., 2021). Also, the presence of compounds in lower concentrations, such as magnesium oxide, free calcium oxide, potassium, and sodium oxides, can result in the obtaining of unwanted chemical compounds and thus alter the expected stoichiometry, manifesting in the alteration of the properties of cement in the fresh and solid state (Merachtsaki et al., 2021). Likewise, carbonates or other types of salts change the chemical reactions to obtain concrete and alter the stoichiometry in the mixture (Štukovnik et al., 2014). Water treatment is categorized by its origin, which can be industrial, agricultural, urban, and domestic. Domestic water has a more straightforward chemical composition and, depending on its content, is differentiated into black water, gray water, and water containing cleaning products (Zhang et al., 2022). Wastewater treatment can be divided into levels, primary or preliminary, where elements in the wastewater with the most significant insoluble particles are removed by mechanical means such as filters or screens. The secondary treatment is responsible for eliminating chemical and biological agents through aerobic and anaerobic actions with the implementation of biological actions. The tertiary therapies, in which physical and chemical processes are carried out, clean the wastewater from contaminants such as minerals, heavy metals, viruses, and surpluses of organic compounds (Wu et al., 2022).

There is a bibliographic record that secondary-treated domestic wastewater has diverse applications in different areas of interest to humanity, for example, irrigation of green regions, agricultural irrigation, filling lakes, and industrial and commercial use (Shukla et al., 2021). However, in the construction sector, controversial results have been detected regarding its mechanical behavior attributed to the mechanical properties of the cementitious material. For example, the research entitled "***Use of treated wastewater for concrete mixing in Kuwait***" reflects the evaluation of concrete cubes manufactured with both potable and residual water with preliminary treatment (elimination of large and insoluble particles in water by mechanical means), secondary treatment (removal of organic matter with the help of biological means) and tertiary treatment (exclusion of bacteria, viruses, heavy metals or colloidal inorganic salts remaining in the secondary-treated domestic wastewater) demonstrating that the physical performance of the specimens are affected by the presence of this type of water (Al-Ghusain et al., 2003). Other investigations have also studied concrete manufactured with secondary-treated domestic wastewater, focusing on the effect of nitrate concentration and its consequence on the physical behavior of concrete, concluding that the presence of nitrate does not represent a problem concerning the permeability of concrete, nor the durability speaking of wear. However, other research has studied the influence of other water chemical conditions, such as pH. The results have shown that high pH levels in water impact the solubility of concrete, and some physical properties of cement may be compromised (such as concrete slump and compressive strength) (Natkunarajah et al., 2022). There are scarce researchers related to the review of the analysis of the use of secondary-treated domestic wastewater to produce concrete, i.e., "Sustainable use of different wastewater in concrete construction: A review" (Varshney et al., 2021) and "Effect of wastewater as sustainable concrete material on concrete performance: A critical review" (Hamada et al., 2023). However, the analysis intends not to delve into the chemical-mechanical relationship between the use of secondary-treated domestic wastewater and its consequences on concrete. In this study, one of the most wastewater generated by humanity, secondary-treated domestic wastewater, is analyzed, considering its chemical characteristics and its impact on the physical capabilities of concrete in the fresh and hardened state. The relevance of this work is to obtain information on the viability of manufacturing concrete using this kind of water, explaining the chemical interactions between concrete components and the chemical conditions present in the secondary-treated domestic wastewater related to pH, salts, hydroxides, and total dissolved solids (TDS). The literature analysis pointed out that the implementation of secondary-treated domestic wastewater is favorable to the production of concrete and proposes some possible perspectives based on the results of the investigations.

3. METHOD

The methodology employed in this study began with identifying previous research focused on the use of secondary-treated wastewater in concrete production. Subsequently, the analysis concentrated on the chemical and mechanical properties potentially affected by this practice. This was accomplished through a comprehensive review of existing literature, wherein various authors reported alterations in the properties of concrete in both its fresh and hardened states. These changes were assessed using standard tests such as slump measurements for the fresh state and compressive and flexural strength tests for the hardened state. Care was taken to include studies with comparable experimental procedures and analytical methods to ensure consistency and reliability in comparing reported results. The study procedure, in general, can be seen in Figure 1.

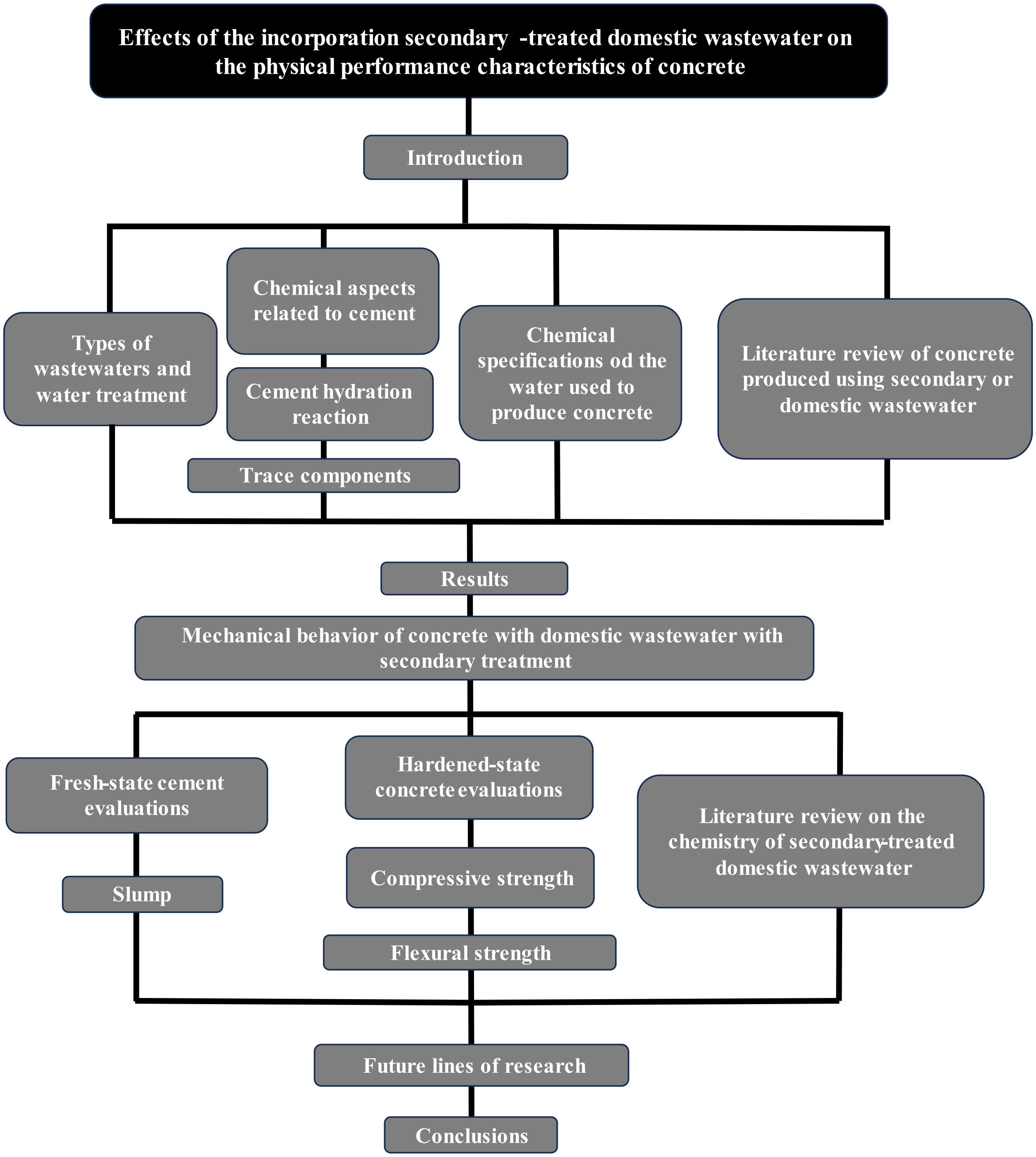

Figure 1. Diagram illustrating the research methodology.

3.1. Types of wastewaters and water treatment.

Water treatment is conventionally defined as the removal of organic and inorganic contaminants to enable reuse and is typically classified into primary, secondary, and tertiary stages according to the complexity of the treatment. While this classification is widely accepted, recent studies have highlighted that it is primarily designed to meet environmental discharge regulations and does not necessarily reflect the suitability of treated effluents for specific engineering applications, such as concrete production (Silva, 2023; Maddikeari et al., 2024). Primary treatment relies on mechanical processes—such as filtration, screening, sedimentation, and flocculation—to remove coarse and settleable solids (Quach-Cu et al., 2018). However, from a materials engineering perspective, this level of treatment is clearly insufficient, as it does not significantly reduce dissolved ions or organic compounds, which are known to directly interfere with cement hydration reactions and early-age behavior. Secondary treatment introduces biological processes in which microorganisms degrade biodegradable organic matter, producing biomass that is subsequently removed as suspended solids (Maizel et al., 2017). Although this stage effectively reduces the organic load (e.g., BOD_5), recent evidence indicates that secondary-treated domestic wastewater still contains significant concentrations of dissolved salts, nutrients, and residual organic matter. These components have been shown to modify hydration kinetics, alter the Ca/Si ratio of hydration products, and affect compressive strength and porosity (Keneshlo et al., 2024). Furthermore, experimental studies report that secondary-treated domestic wastewater can delay setting time and influence phase development, as observed through X-ray diffraction analysis (Micheal and Abd El Salam, 2024). Tertiary treatment involves advanced physicochemical processes—including precipitation, chlorination, reverse osmosis, and UV radiation—to remove residual contaminants such as nutrients, heavy metals, and pathogens (Zagklis et al., 2022). Despite its greater efficiency, this level of treatment is not always implemented due to economic and operational constraints. More importantly, even tertiarily treated effluents can retain ionic species, such as chlorides and sulfates, at concentrations sufficient to affect durability-related processes in cementitious systems. For example, recent studies have shown that these ions can modify hydrated products, influence microstructure, and increase susceptibility to expansion or long-term degradation (Micheal and Abd El Salam, 2024; Maddikeari et al., 2024). A critical limitation of conventional classification is that it does not account for variability in chemical composition across effluents at the same treatment stage. Recent literature consistently demonstrates that the performance of concrete incorporating secondary-treated domestic wastewater depends largely on pH, ionic strength, and residual organic content, rather than solely on the treatment stage (Keneshlo et al., 2024; Maddikeari et al., 2024). Furthermore, conflicting findings have been reported: some studies indicate increased porosity and delayed hydration, while others suggest potential densification effects due to the filler's action or biological activity (Soltanianfard et al., 2023; Hamada et al., 2023). This variability highlights a significant deficiency in current classification approaches.

Figure 2 illustrates the classification of wastewater and its corresponding treatment stages; however, it should be interpreted with caution. The level of treatment alone is not a reliable indicator of suitability for concrete applications. Instead, a more robust framework is required that integrates secondary-treated domestic wastewater chemistry with cement hydration mechanisms and durability. This perspective is essential to bridge the gap between environmental engineering classifications and specific material requirements.

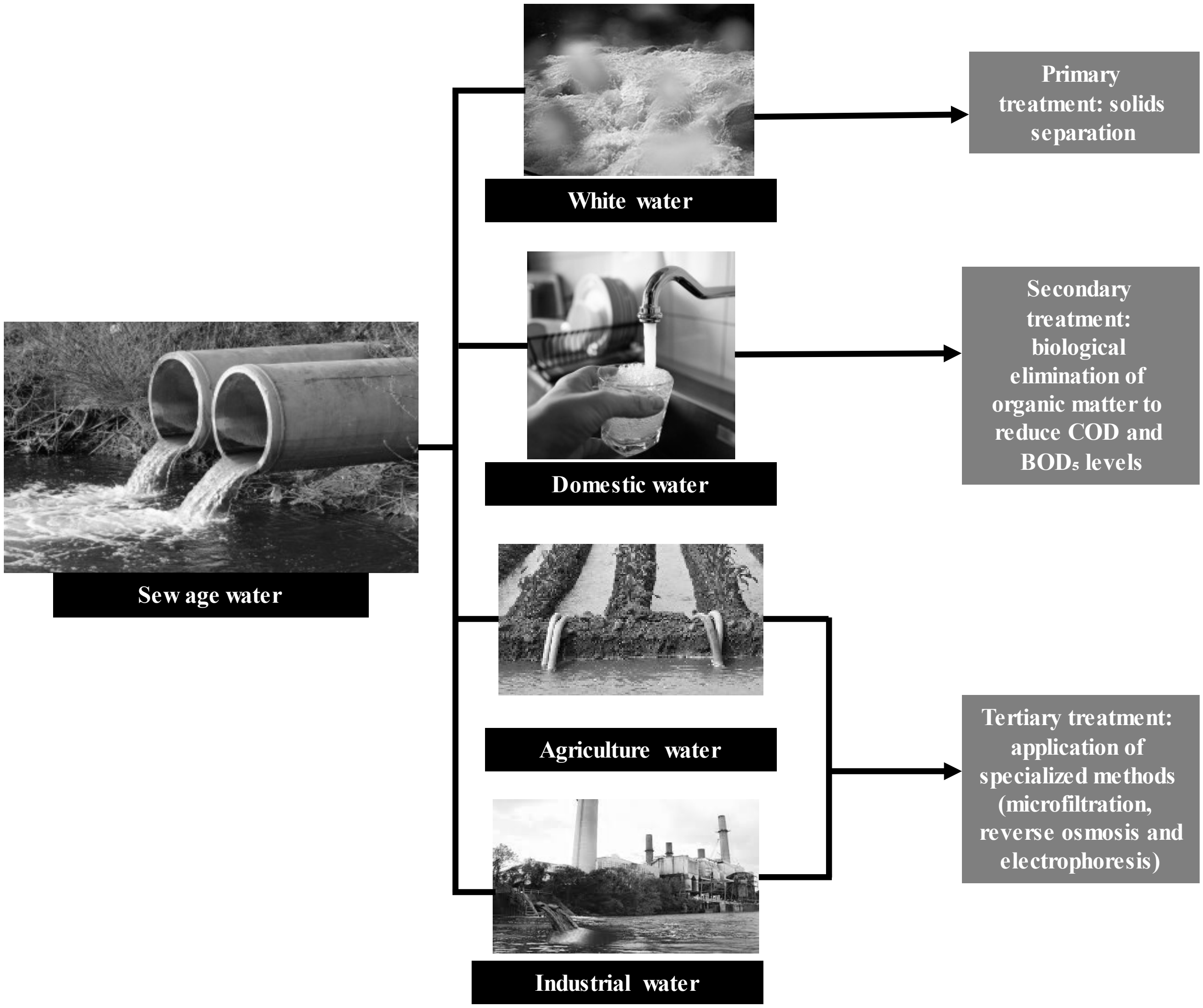

Figure 2. Diagram of the type of wastewater. COD stands for Chemical Oxygen Demand, and BOD_5 stands for Biological Oxygen Demand: Adapted from: Widyarani et al., 2022.

3.2. Chemical properties and composition of cement.

Cement is produced by heating a mixture of limestone and clay in large rotary kilns at high temperatures. This process yields clinker, a material composed primarily of silica, calcium, alumina, and iron. The clinker becomes cement when ground and mixed with gypsum (Coffetti et al., 2022). Figure 3 provides an overview of the key chemical reactions in cement production. The process begins with raw materials rich in calcium, silica, alumina, and iron. Figure 3 shows the complete diagram for obtaining cement.

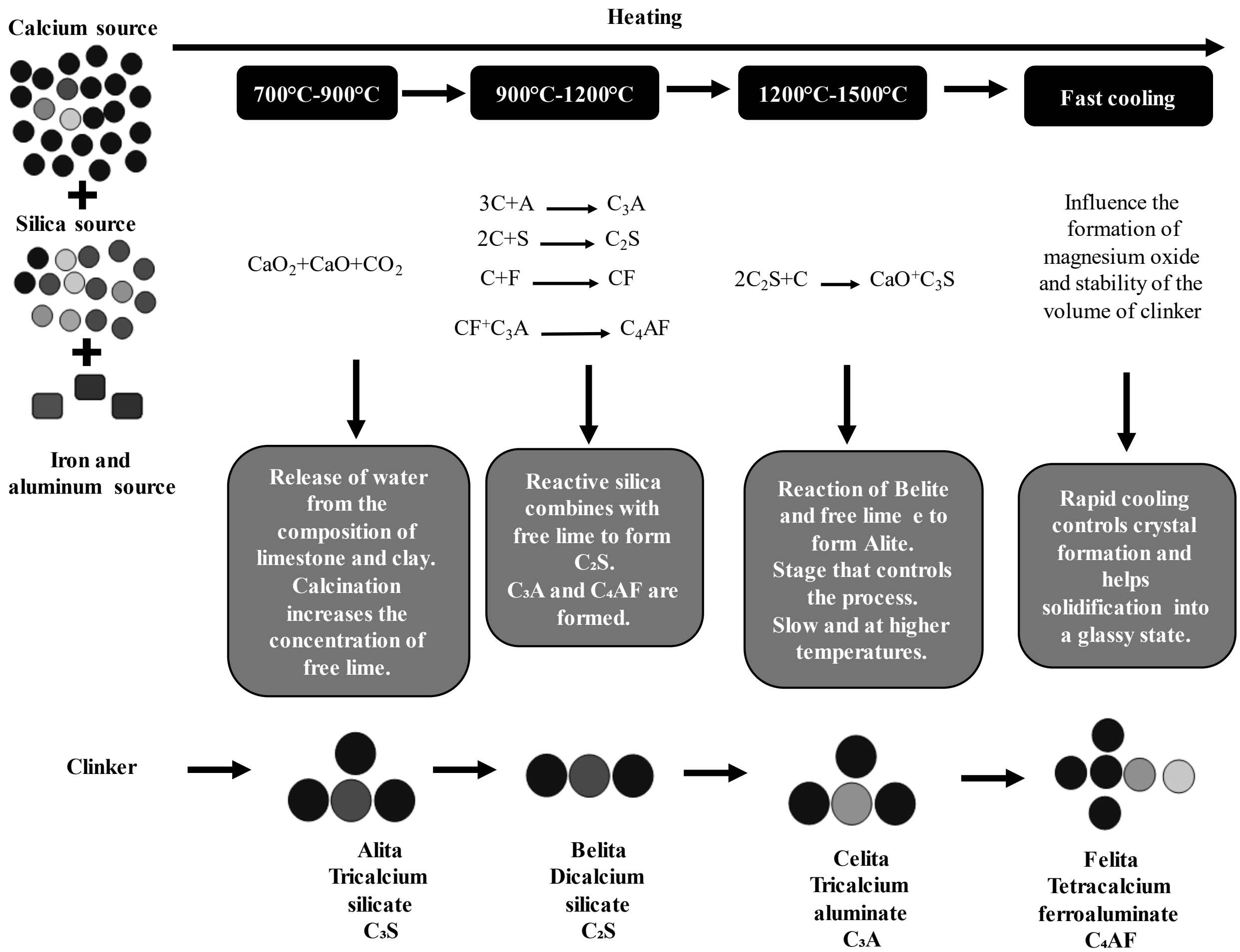

Figure 3. Chemical process to obtain cement. Adapted from: Mache et al., 2025.

While the reactions involved in clinker formation and hydration (Figure 3) are well documented in the literature, their behavior can be significantly altered when secondary-treated domestic wastewater is used as mixing water. Therefore, critical analysis should focus not on the reactions themselves, but on how the components of secondary-treated domestic wastewater alter their kinetics, products, and stability.

The hydration of alite (C_3S) and belite (C_2S), which determines strength development, is particularly sensitive to the ionic species present in secondary-treated domestic wastewater. Recent studies have confirmed that variations in pH and ionic composition directly influence the Ca/Si ratio of the hydration products and, consequently, the compressive strength and microstructure. Acidic conditions tend to reduce strength and increase porosity, while more alkaline conditions promote more stable hydration products. This demonstrates that even fundamental reactions such as C_3S hydration are highly dependent on the chemical environment provided by the mixing water (Keneshlo et al., 2024).

Chloride and sulfate ions, commonly present in secondary-treated domestic wastewater, play a key role in modifying clinker phase reactions. Chlorides can accelerate initial hydration but, at the same time, introduce risks to long-term durability, particularly in reinforced systems. Sulfates, on the other hand, directly affect C_3A reactivity, leading to excessive ettringite formation and expansion. Recent experimental evidence shows that concrete produced with secondary-treated domestic wastewater exhibits greater expansion under sulfate exposure, confirming that these ions significantly alter phase stability and durability (Micheal and Salam, 2024).

From a microstructural perspective, the presence of dissolved solids and organic matter in secondary-treated domestic wastewater further complicates the system. Some studies indicate that these components can delay hydration and increase porosity, while others point to potential densification effects from microbial fillers or byproducts that reduce pore connectivity. This apparent contradiction highlights a key gap in current knowledge: the impact of secondary-treated domestic wastewater is not universal but depends largely on its composition and level of treatment (Arooj et al., 2021).

Recent research has also highlighted the role of specific contaminants such as nitrites, chlorides, and sulfates in disrupting hydration mechanisms. High concentrations of these substances can accelerate initial hydration, but in the long term, they cause microstructural instability, increased susceptibility to carbonation, and greater porosity. These findings are particularly relevant because they demonstrate that the classical reactions shown in Figure 3 do not fully reflect the dynamic chemical interactions that occur in secondary-treated domestic wastewater systems (Soltanianfard et al., 2025).

Furthermore, advanced characterization techniques (e.g., XRD, SEM, and EDS) have revealed that secondary-treated domestic wastewater can modify the crystalline phases and hydration products formed during cement hydration, leading to detectable changes in peak intensities and compound distribution. This provides direct evidence that reaction pathways are not only kinetically affected but can also result in different phase sets (Micheal and Salam, 2024).

Another limitation of conventional clinker reaction diagrams is the lack of consideration for the interfacial transition zone (ITZ). Recent studies indicate that secondary-treated domestic wastewater can influence ITZ properties by introducing fine particles and dissolved components that, depending on their chemical composition, either increase packing density or weaken interfacial bonding. This further reinforces the idea that macroscopic behavior cannot be predicted solely from clinker-phase reactions.

In general, while Figure 3 accurately represents the fundamental chemistry of clinker formation and hydration, it does not account for the variability introduced by secondary-treated domestic wastewater. Recent literature consistently demonstrates that its components actively modify hydration kinetics, phase stability, and microstructure, though sometimes with contradictory results depending on secondary-treated domestic wastewater composition. Therefore, future research should systematically link wastewater chemistry to cement hydration mechanisms to better predict cement performance and durability.

3.3. Cement hydration reaction and trace components.

Cement is a binding material primarily composed of calcium compounds and clay minerals. Upon hydration, cement transitions from dry powder to paste and subsequently hardens when exposed to air or water.

Figure 4 illustrates the sequential stages of the cement hydration process.

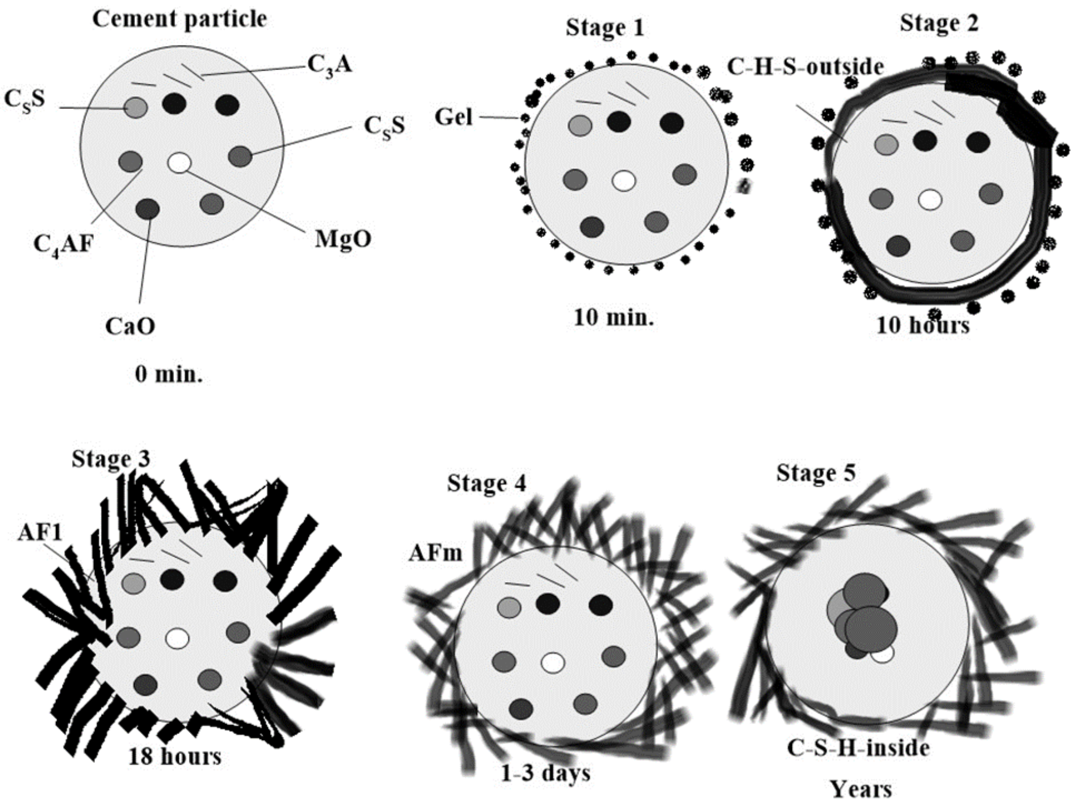

Figure 4. Cement hydration reaction process. Adapted from: John and Lothenbach, 2023.

Figure 4 illustrates the classical stages of cement hydration, including the initial dissolution (Stage 1), formation of C–S–H and portlandite (Stage 2), development of ettringite (AFt, Stage 3), transformation to monosulfate (AFm, Stage 4), and long-term densification of C–S–H (Stage 5). While these stages are well established, their progression and stability can be significantly modified when secondary-treated domestic wastewater is used as mixing water (Bullard et al., 2011).

In the initial stages (stages 1-2), the interaction between cement particles and water governs dissolution and nucleation. Studies indicate that the presence of organic matter and dissolved impurities in secondary-treated domestic wastewater can delay both the initial and final setting times, suggesting a slowdown in the early hydration kinetics and C-S-H nucleation. This effect complements the discussion in Figure 3, where the clinker phase reactions are shown as invariant, when their kinetics are highly sensitive to the chemical environment (Micheal and Salam, 2024).

During Stage 2 (10 h), when C–S–H begins to form around the cement grains, recent X-ray diffraction analyses demonstrate that, although the same hydration products form, their relative intensities and crystallinity differ when secondary-treated domestic wastewater is used. This indicates that the reaction pathways shown in Figure 3 remain valid, but the degree of reaction and phase development is modified. These modifications directly affect the initial mechanical performance and microstructural evolution (Micheal and Salam, 2024).

In stage 3 (18 h), associated with the formation of AFt (ettringite), the influence of sulfate ions becomes crucial. As shown in Figure 3, sulfates in secondary-treated domestic wastewater can either enhance or destabilize ettringite formation, depending on their concentration. Experimental evidence shows that greater sulfate availability can lead to greater expansion and potential durability problems due to excessive formation of expansive phases. This underscores that AFt formation depends not only on the cement composition but also on external sulfate sources (Soltanianfard et al., 2025).

The AFt to AFm transition (Stage 4, 1–3 days) is particularly sensitive to ionic equilibrium. Variations in sulfate and aluminate availability, modified by secondary-treated domestic wastewater, can alter equilibrium conditions, delaying or altering the conversion process. This is consistent with findings indicating that hydration reactions in contaminated systems exhibit altered kinetics and phase stability, especially in the presence of competing ions such as chlorides and nitrites (Soltanianfard et al., 2025). As shown in Figure 3, these ions also affect the C_3A reactions, reinforcing the interdependence between the two figures.

During prolonged curing times (Stage 5), where C–S–H densification predominates, the role of secondary-treated domestic wastewater becomes even more complex. Some studies report increased porosity due to delayed hydration and organic interference, while others indicate lower porosity and improved compaction due to microbial activity or fine suspended particles acting as fillers. This dual behavior reveals a key limitation of classical hydration models: they do not account for the biologically or chemically active species present in secondary-treated domestic wastewater (Arooj et al., 2021).

Furthermore, the thermal evolution during hydration appears to be only marginally affected, suggesting that the fundamental exothermic nature of hydration is preserved even when using secondary-treated domestic wastewater. However, slight variations in temperature profiles and heat evolution have been linked to residual impurities and reactive particles in the water, suggesting subtle yet significant changes in reaction kinetics (ElGazzar et al., 2024).

3.4. Standards and permissible limits for water used in concrete.

Several researchers have highlighted that the secondary-treated domestic wastewater used in concrete production must contain minimal concentrations of chemical species that could interfere with cement hydration and strength development (Junsomboon and Jakmunee, 2011). According to international standards, particularly ASTM C1602 (ASTM International, 2018), mixing water must meet specific quality requirements to prevent it from adversely affecting the properties of fresh or hardened concrete. ASTM C1602 (ASTM International, 2018) establishes acceptance criteria based on chemical limits or performance tests. Typical reference values include chloride contents in the range of 500 to 1000 ppm (depending on the type of concrete and exposure conditions), sulfate concentrations up to approximately 3000 ppm, alkalis (expressed as Na_2O + 0.658 K_2O) around 600 ppm, and total dissolved solids (TDS) up to 50,000 ppm (ASTM, 2018). However, it is important to note that ASTM C1602 is not based solely on fixed limits. It also allows the use of secondary-treated domestic wastewater if comparative tests (e.g., compressive strength and setting time) demonstrate acceptable performance. This performance-based approach is often overlooked in literature. Other standards, such as ACI 318 (American Concrete Institute, 1995), BS 1008 (British Standards Institution, 2002), and IS 10262:2009 (Indian Bureau of Standards, 2009), also define permissible chemical limits to prevent adverse interactions with cement hydration. These standards systematically identify chlorides, sulfates, alkalis, and dissolved solids as critical parameters. Chloride ions are typically limited to approximately 500 ppm for reinforced concrete due to their role in promoting corrosion, while sulfates are restricted to prevent the expansion and cracking associated with late ettringite formation. Alkalis are controlled to mitigate alkali-aggregate reactions, and total dissolved solids (TDS) limits aim to prevent undesirable changes in pH and hydration chemistry. Despite this apparent consensus, a critical limitation of these standards is that they are based primarily on potable water equivalence or simplified chemical thresholds, without fully considering the complex composition of secondary-treated domestic wastewater sources, such as secondary-treated domestic wastewater. Recent studies have shown that even when these limits are met, variations in ionic composition, organic content, and pH can influence hydration kinetics, phase development, and long-term durability. For example, chloride and sulfate ions can simultaneously accelerate initial hydration and negatively impact durability,

indicating that compliance with individual thresholds does not guarantee optimal performance. Furthermore, most standards treat each parameter independently, whereas in real-world systems, especially when using secondary-treated domestic wastewater chemical species interact synergistically. The combined presence of chlorides, sulfates, and residual organic matter can produce effects that cannot be predicted from individual limits alone. This highlights a gap between standardized acceptance criteria and the actual behavior of materials. Another significant limitation is that these standards were developed primarily for conventional concrete and potable or slightly contaminated water sources. Consequently, they do not explicitly address emerging sustainability practices, such as the reuse of secondary-treated domestic wastewater, where compositional variability is significantly greater. In this context, recent literature supports the adoption of performance-based assessment methods—such as strength, setting time, and durability tests—rather than relying strictly on chemical thresholds. Finally, pH remains a critical parameter, as it governs the solubility and reactivity of ionic species during cement hydration. While standards generally recommend neutral or slightly alkaline conditions, deviations associated with high levels of dissolved solids or residual chemicals from the treatment process can disrupt hydration mechanisms and lead to undesirable physical and mechanical properties. Therefore, pH should not be considered in isolation, but rather as part of an integrated chemical system.
In summary, while existing standards provide a necessary framework for assessing water quality in concrete production, they have significant limitations when applied to water sources.

3.5. Evolution of the literature on concrete made with secondary-treated domestic wastewater.

Research on the use of secondary-treated domestic wastewater in concrete began in the 1980s (Cebeci et al., 1989) but gained prominence in the 2000s with advances in water-quality analysis and testing methods. Key studies, mainly from India, by Al-Ghusain and Terro (2003) and Noruzman et al. (2012), examined chemical parameters such as TSS, sulfates, chlorides, pH, BOD_5, and COD, determined using standard methods for water analysis, including gravimetric determination of total suspended solids (TSS), titration methods for chlorides, spectrophotometric analysis for sulfates, and standardized procedures for BOD_5 and COD (e.g., respirometric and dichromate oxidation methods), with the number of tests per study ranging from 10 to 19.
Over time, the research became more specific, emphasizing analytical rigor. All studies systematically evaluated the setting time, compressive strength, and slump of concrete using standardized procedures, such as the Vicat needle test for setting time, compression tests for strength, and the Abrams cone test for workability, confirming that these are the most relevant mechanical properties when using secondary-treated domestic wastewater. Studies, including those by Swami et al. (2015), Ghrair et al. (2018), and Asadollahfardi et al. (2016), have expanded concrete assessment methods beyond conventional testing to include advanced techniques such as scanning electron microscopy (SEM) for microstructural analysis, X-ray-based techniques (e.g., XRF/EDS) for elemental characterization, porosity assessment using mercury intrusion porosimetry (MIP), freeze-thaw resistance testing, and ultrasonic pulse velocity (UPV) measurements to evaluate internal integrity. Innovations by Meena and Luhar (2019) also introduced the determination of carbonation depth (using indicator methods), chloride migration testing, and abrasion resistance assessments. Chemical analyses have increasingly focused on dissolved salts and pH-modifying species, which are generally quantified by titration or chromatography, due to their direct influence on cement hydration and mechanical behavior. Overall, testing has evolved toward more specific, methodologically sound experimental approaches, thereby increasing the reliability of using secondary-treated domestic wastewater in concrete production.

3.6. Mechanical behavior of concrete made with secondary-treated domestic wastewater.

3.6.1. Fresh-state cement evaluations.

3.6.1.1 Slump.

Concrete workability in its fresh state is typically assessed using the slump test, which reflects the mixture's consistency and secondary-treated domestic wastewater content. Studies such as those by Al-Ghusain, and Terro (2003), More et al., (2014), Ramkar and Ansari (2014), and Swami et al., (2015), reported no significant differences in slump between concrete made with secondary-treated domestic wastewater and that made with potable water. However, other studies, including those by Meena and Luhar (2019), Noruzman et al., (2012), Ghrair et al., (2018), and Asadollahfardi et al., (2016), observed reduced workability, with slump reductions of 50%, 40%, 19%, and 10%, respectively. Table 1 summarizes slump-related mix designs using secondary-treated domestic wastewater. These investigations, primarily conducted in Asia—especially India (62.5%)—reflect regional environmental concerns and openness to sustainable alternatives. Standard mix characteristics include secondary-treated domestic wastewater usage ranging from 150–400 kg/m³, a water/cement ratio of 0.4–0.62, cement content between 300–445 kg/m³, fine aggregates from 200–631 kg/m³, and coarse aggregates between 514.7–1159.5 kg/m³. Notably, 75% of the studies used sand and granite as the primary aggregates.

Table 1. Summary of the design of concrete with secondary-treated domestic wastewater for slump tests.

Reference	Aggregates (mm)	Water (kg/m^3)	Ratio water/ cement	Module fineness	Cement (kg/m^3)	Fine aggregates (kg/m^3)	Coarse aggregates (kg/m^3)	Origin of water
Al-Ghusain, and Terro (2003)	20	200	0.62	-	-	-	-	Reqqa, Kuwait
Noruzman et al., (2012)	Granite: 10 Sand: 5	-	-	Sand: 2.40	-	-	-	-
More et al, (2014)	-	-	-	-	-	-	-	Mundhwa, Pune, India
Swami et al., (2015)	S-G: 10 y 20	178	0.4	3.25	445	628	10 mm: 523 20 mm: 777	Vasant Kunj, New Delhi, India

	S-G: 10 y 20	196	0.5	5.92	392	628	10 mm: 523 20 mm: 777	Vasant Kunj, New Delhi, India
Ramkar and Ansari (2016)	20	-	0.45	-	-	-	-	Shirdi, Maharashtra, India
Ghrair et al., (2018)	S-G: 9.50 (Hemseye) 4.73 (Adaseyeh) S-G: 2.36 (Semsmey) 0.30 (Sand)	233	NE INR	4.95 (Hemseyeh) 5.03 (Adaseyeh) 4.96 (Semsmeyh) 1.83 (Sand)	418.2	502.7 (Sand) 252.1 (Semsmeye)	514. 7 (Hemseh) 370.3 (Adaseyeh)	Jaipur, India
Asadollahfardi et al., (2016)	-	C300: 180	C300: 0.6	-	30	212 (Sand)	C300: 797 (Gross sand) 900 (Gravel)	Khoramabad, Lorestan, Iran
	-	C350: 150	C350: 0.43	-	350	214 (Sand)	C350: 818 (Gross sand) 880 (Gravel)	Khoramabad, Lorestan, Iran
	-	C400: 200	C400: 0.5	-	400	200 (Sand)	C 400: 734 (Gross sand) 80 (Gravel)	Khoramabad, Lorestan, Iran
Meena and Luhar (2019)	S-G: 20	189.7	0.47	3.15	395	631	1159.5	Jaipur, India

Table 2 presents the slump results for concrete produced with 100% secondary-treated domestic wastewater, except for Ahmad and Ayyad (2021), who used 25–100% proportions. Control slump values ranged from 75 mm to 160 mm (reported in 91.66% of studies), while mixes with secondary-treated domestic wastewater ranged from 30 mm to 120 mm. A reduction in workability was observed in 41.66% of cases. ASTM C143 (ASTM International, 2012), BS EN 12350 (British Standards Institution, 2019) conducted the tests, IS 7320-1974 (Bureau of Indian Standards, 1974), and IS 1199-1959 (Bureau of Indian Standards, 1959). Based on the IS 1199 classification, 33% of results fall within medium workability, 17% in low, and 50% in high slump range (Bureau of Indian Standards, 1959).

Table 2. Summary of workability results in concrete with secondary-treated domestic wastewater.

References	Percentage of secondary-treated domestic wastewater	Slump control (mm)	Wastewater slump (mm)	Reference standard	IS 1199 Workability
Al-Ghusain, and Terro (2003)	100	75	70-80	-	Medium
Noruzman et al., (2012)	100	50	30	BS EN 12350 (Institution, 2009)	Low
More et al., (2014)	100	90-100	90-100	-	Medium
Swami et al., (2015)	100	120	120	-	High
	100	120	120	-	High
	100	120	120	-	High
Ramkar and Ansari (2016)	100	90-100	90-100	IS 7320-1974 (Standards, 1974)	Medium
Ghrair et al., (2018)	100	160	130	BS EN 12350 (Institution, 2009)	High
Asadollahfardi et al., (2016)	A300: 100	C300: 110	C300: 99	ASTM C143 (ASTM International, 2012)	High
	C350: 100	C350: INR	C350: 105	ASTM C143 (ASTM International, 2012)	High
	C400: 100	A400: 90	C400: 82	ASTM C143 (ASTM International, 2012)	Medium
Meena and Luhar (2019)	100	80	40	IS 1199-195 (BIS, 1959)	Low

3.6.2. Hardened-state concrete evaluations.
3.6.2.1. Compressive strength.
Compressive strength is a key property for assessing the hardened performance of concrete. Studies on concrete produced with secondary-treated domestic wastewater have reported mixed results, primarily influenced by the chemical composition of the water, especially concentrations of chlorides, sulfates, nitrates, carbonates, and total solids. Several studies have shown varying effects on the compressive strength of concrete made with secondary-treated domestic wastewater. Al-Ghusain, and Terro (2003) reported reductions of 12%, 3%, 8%, and 3% at 21, 180, 365, and 548 days due to high concentrations of solids, sulfates, chlorides, and alkalinity (pH 7.8). Noruzman et al., (2012) found reductions of 11% at 7–14 days and 4% at 60 days. More et al., (2014) observed a 10% drop in early strength but a slight recovery (+3%) by day 60. Asadollahfardi et al., (2016) noted 3–9% reductions at various curing stages. Meena and Luhar (2019) found significant decreases of 32%, 28%, and 16% at 7, 28, and 90 days. Ahmad and Ayyad (2021) showed mixed results based on secondary-treated domestic wastewater percentages; a 100% secondary-treated domestic wastewater mix led to early-age strength loss (up to 27%) but recovery over time, while 25% secondary-treated domestic wastewater resulted in strength gains up to 38%. On the other hand, Ghrair et al., (2018) found no significant difference in strength up to 200 days. Despite high alkalinity and dissolved solids, Swami et al., (2015) reported 6–8% strength increases across varying water/cement ratios. Ramkar and Ansari (2016) observed gains of 4–11% at 7, 28, and 60 days, linked to low levels of aggressive salts and an acidic pH of 6.41. Overall, these results highlight that the chemical composition of the secondary-treated domestic wastewater—not merely determines its compressive strength outcomes. Higher concentrations of sulfates, chlorides, nitrates, and alkalinity typically reduce performance, while balanced or lower concentrations can enhance hydration and strength. Figure 5 presents a comparative analysis of compressive strength between concrete made with secondary-treated domestic wastewater and tap water. The bars indicate the change in strength, with positive numbers representing an increase and negative numbers showing a reduction in strength. A value of 0, although indicative of no difference in performance between the concrete with secondary-treated domestic wastewater and the control, is not represented in the data shown.

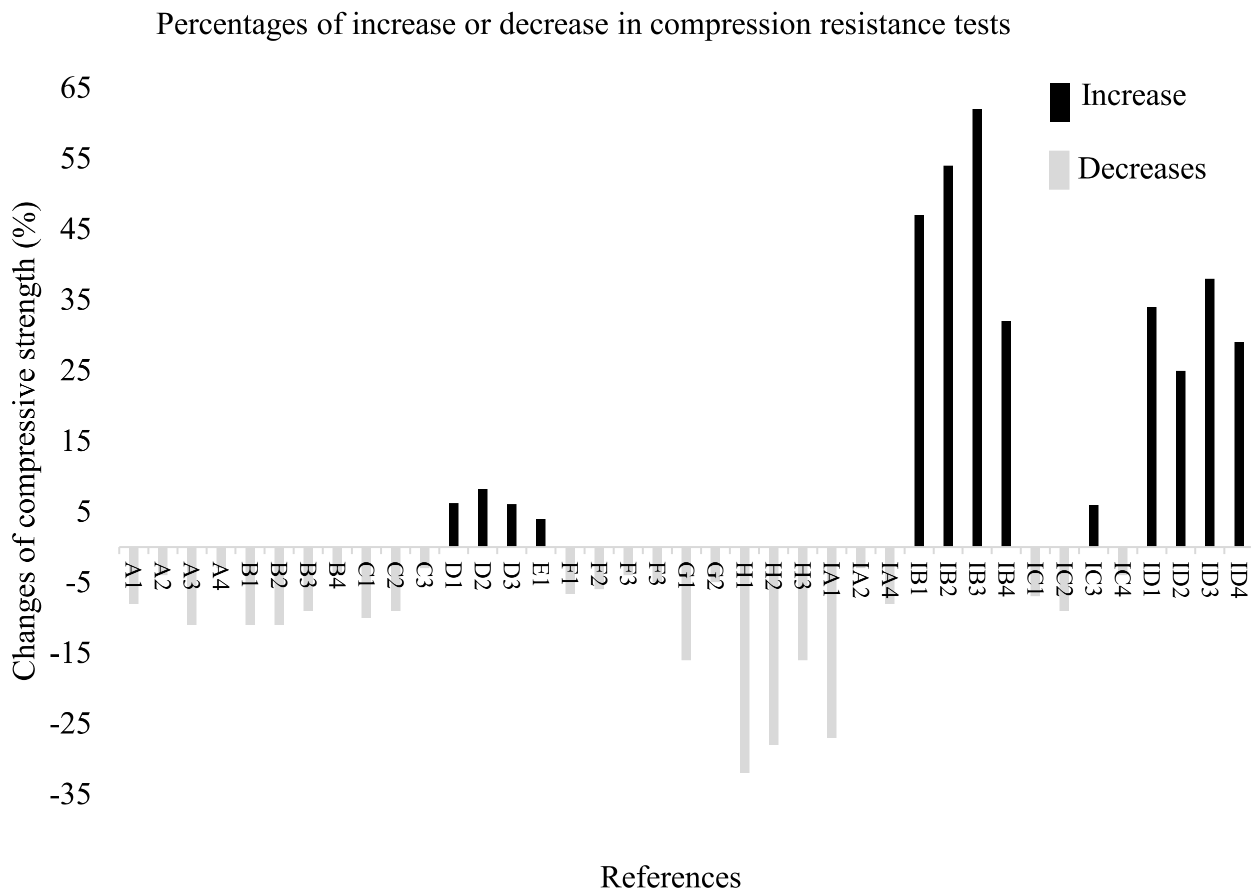

Figure 5. Percentages of increase or decrease in compression resistance tests. A: Al-Ghusain and Terro, (2003), B: Noruzman et al., (2012), C: More et al., (2014), D: Swami et al., (2015), E: Ramkar and Ansari, (2016), F: Ghrair et al. (2018), G: Asadollahfardi et al., (2016), H: Meena and Luhar, (2019). I: Ahmad and Ayyad, (2021). The order of appearance of the samples mentioned in each investigation.

Figure 6 illustrates the overall trend of compressive strength changes. The data reveals that 59% of the samples showed a decrease in strength, 27% showed an increase, and 14% demonstrated similar behavior between concrete with secondary-treated domestic wastewater and control specimens.

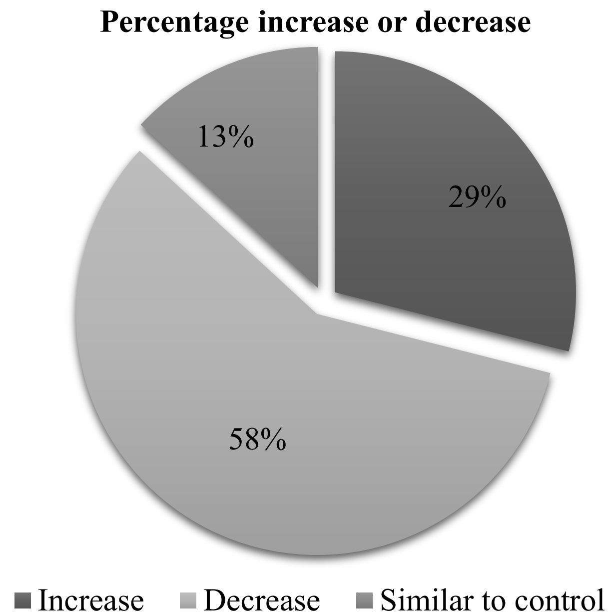

Figure 6. Percentages of increase or decrease in compression resistance tests.

3.6.2.2. Flexural strength.

Flexural strength in concrete made with secondary-treated domestic wastewater is typically influenced by the presence of chemicals like chlorides, sulfates, and nitrates, which can degrade performance (Kucche et al., 2015). Studies report mixed results. Meena and Luhar (2019) observed significant reductions in flexural strength (45% at 28 days, 19% at 90 days). Similarly, Ramkar and Ansari (2016) noted an 11% decrease, attributed to the water's acidic pH and high hardness. However, More et al., (2014) found a 4.32% improvement in flexural strength in 28 days, demonstrating that secondary-treated domestic wastewater could enhance mechanical performance in some cases.

3.7. Literature review on the chemistry of secondary-treated domestic wastewater.

Different regulations specify the properties that conventional water must meet for concrete production, with key standards such as IS 516 (Bureau of Indian Standars, 1959), 1199 (Bureau of Indian Standars, 1959), BS 1008 (British Standards Institution, 2002), and ASTM C1602 (ASTM, 2018) being widely referenced. However, no specific regulations exist for using secondary-treated domestic wastewater in concrete. Consequently, most studies base the chemical characterization of such wastewater on tap water standards. As reported in the literature, the chemical findings of secondary-treated domestic wastewater are as follows. Studies on secondary-treated domestic wastewater show it generally meets the chemical requirements for concrete production, as outlined by various standards. Asadollahfardi et al., (2016) and Al-Ghusain and Terro (2003) identified several key chemical characteristics (pH, total dissolved solids, suspended solids, nitrates (NO_3^-), and sulfates (SO_4^{-2}) in treated wastewater that align with ASTM C94 (ASTM International, 2020) and APHA standards (American Public Health Association et al., 2017). While some tests showed slightly higher values in parameters such as total solids and alkalinity than conventional water, the secondary-treated domestic wastewater still complied with relevant limits for concrete use. Noruzman et al., (2012) and More et al., (2014) observed that parameters like pH, alkalinity, and suspended solids in treated wastewater fell within the acceptable ranges for concrete production. However, some instances of non-compliance were noted, such as pH levels and hardness. Swami et al., (2015) found that characteristics like total solids, chlorides, and sulfates in the secondary-treated domestic wastewater adhered to ASTM C1602 (ASTM International, 2018), and IS 456 standards (Bureau of Indian Standards, 2000) with the water's chemical composition broadly acceptable for concrete mixtures. Some researchers have found that secondary-treated domestic wastewater often meets or surpasses the chemical quality of tap water. For instance, Ramkar and Ansari (2016) reported that the secondary-treated domestic wastewater had a pH of 6.41, slightly less acidic than the control water (pH 6.18), falling outside the BIS 456 (Bureau of Indian Standards, 2000) and 516 standards (Bureau of Indian Standards, 1959), pH range of 6.5–8.5. The secondary-treated domestic wastewater had significantly lower total dissolved solids (TDS) than the control, well below the standard's 100 mg/l limit. Although the hardness of the secondary-treated domestic wastewater (35 mg/l) exceeded the control (12 mg/l), it remained within the BIS standard of 300 mg/l. Both biological oxygen demand (BOD_5) and chemical oxygen demand (COD) were much lower in secondary-treated domestic wastewater, with values of <10 mg/l and 100 mg/l, respectively, well below the BIS standard limits. In contrast, other studies highlighted several chemical parameters that did not meet international standards. Ghrair et al., (2018) was found that while most parameters complied with the requirements of ASTM C94 (ASTM International, 2020), BOD_5 (2.98 mg/L) and ammonia (4.5 mg/L) exceeded the typical concentrations reported for drinking water by the World Health Organization, <0.2–0.5 mg/L (WHO, 2017). Meena and Luhar (2019) reported that BOD_5 in treated wastewater was 20 mg/l, still within acceptable limits, though the turbidity was higher (0.305 NTU) than the control water (0.10 NTU). The pH of secondary-treated domestic wastewater (7.48) was more acidic than the control (8.16), but both were within the ASTM and IS 1199 standards (pH 7–8.5). However, the conductivity of treated wastewater (1.59 mS/cm) exceeded the WHO, which requires 0.05 – 1.5 mS/cm (WHO, 2017). Finally, Ahmad and Ayyad (2021) reported that secondary-treated domestic wastewater exceeded the control water in total dissolved solids, suspended solids, and chlorides, although all values were within standard limits. However, the BOD_5 concentration was notably higher in secondary-treated domestic wastewater (427 times the control), violating World Health Organization (WHO, 2017). requirements. These findings indicate that while secondary treated wastewater can meet many regulatory standards, attention must be paid to parameters like BOD_5, ammonia, turbidity, and conductivity that may exceed allowable limits, potentially impacting its use in concrete production.

3.8. Future lines of research.

The literature highlights various strategies to improve the mechanical performance of concrete using secondary-treated domestic wastewater, primarily focusing on chemical adjustments that influence strength development. While this approach has allowed for the identification of key parameters, such as compressive and flexural strength, as well as the role of sulfates, chlorides, total dissolved solids, and pH, recent studies suggest that future research should move beyond isolated chemical effects and focus on integrated solutions that combine chemical and mechanical optimization (Pramanik et al., 2024). A promising line of research is the incorporation of steel fibers into concrete (SFRC) to mitigate potential reductions in mechanical performance associated with the use of secondary-treated domestic wastewater. Steel fibers are well known for improving tensile strength, ductility, toughness, and crack resistance by bridging microcracks and delaying their propagation (Abbas et al., 2018; Wang et al., 2021). These improvements are particularly relevant in systems where secondary-treated domestic wastewater can alter hydration kinetics, increase porosity, or affect the homogeneity of the cement matrix. Recent studies have shown that steel fibers can significantly improve the mechanical properties of concrete, including compressive, tensile, and flexural strength, as well as its post-cracking behavior and energy absorption capacity (Vijayan et al., 2022; Alshboul et al., 2023; Isabai et al., 2023). These improvements suggest that fiber reinforcement can act as a compensatory mechanism for potential weaknesses arising from the use of secondary-treated domestic wastewater sources. Fiber-reinforced systems have demonstrated better crack control and lower permeability, critical factors for concrete exposed to varying chemical environments (Sun et al., 2023; Wang et al., 2025). Although studies directly combining steel fibers with secondary-treated domestic wastewater are still limited, emerging research on fiber-reinforced concrete incorporating secondary-treated domestic wastewater indicates that fibers can improve fracture toughness and durability, even when the matrix is affected by secondary-treated domestic wastewater chemistry (Maddikeari et al., 2024; Akeb et al., 2025). These findings support the hypothesis that steel fibers can mitigate the adverse effects of secondary-treated domestic wastewater use, particularly on crack propagation and structural integrity. From a durability perspective, the use of steel fibers also offers advantages in aggressive environments. Steel fiber-reinforced concrete has been shown to exhibit greater resistance to shrinkage cracking, freeze-thaw cycles, and carbonation, thereby improving long-term performance (Yoo and Yoon, 2015; (Yu et al., 2025). However, the presence of chlorides in secondary-treated domestic wastewater raises concerns about corrosion of steel fibers, which could compromise their durability over time. This underscores the need for further research into corrosion-resistant fibers or protective strategies, such as coatings or hybrid fiber systems. In addition to the use of commercially available steel fibers, recent research has explored the potential of alternative and recycled fibers as reinforcement in cementitious systems incorporating secondary-treated domestic wastewater. In this context, a recent study by Silva Martínez et al., 2025 investigated the chemical-mechanical behavior of mortars prepared with different concentrations of secondary-treated domestic wastewater and reinforced with commercial and recycled steel fibers derived from tire waste. Their findings demonstrated that pull-out resistance, a key indicator of fiber-matrix interaction, performed favorably, particularly at a 50% replacement level of secondary-treated domestic wastewater. This suggests that recycled steel fibers can achieve adequate adhesion and mechanical contribution even in chemically modified environments. These results open a promising line of research on the combined use of secondary-treated domestic wastewater and recycled fiber reinforcement, not only to improve mechanical performance but also to enhance sustainability through waste valorization. Future studies should investigate in greater depth the long-term durability, corrosion behavior, and interfacial transition zone (ITZ) characteristics of these systems, and optimize fiber dosage and secondary-treated domestic wastewater concentration to achieve a balance between mechanical performance and durability. This integrated approach could significantly contribute to the development of more sustainable and durable concrete materials. Furthermore, future research should adopt a multiparametric, performance-based approach, integrating:

- Chemical composition of secondary-treated domestic wastewater;
- Fiber characteristics (type, geometry, dosage, and distribution);
- Mechanical performance (strength, toughness, crack resistance);
- Durability indicators (corrosion resistance, permeability, resistance to chemical attack).

This approach would allow for the development of optimized mix designs that not only compensate for the variability introduced by secondary-treated domestic wastewater but also improve the overall performance of concrete systems.

In summary, while current research tends to focus on either chemical or mechanical aspects independently, the combined use of secondary-treated domestic wastewater and steel fiber reinforcement offers a promising, underexplored line of research. Integrating these approaches could significantly improve concrete's mechanical performance and durability, contributing to more sustainable and resilient construction practices.

4. CONCLUSIONS

This review demonstrates that incorporating secondary-treated domestic wastewater into concrete production is a technically viable and environmentally relevant alternative; however, its effects on concrete performance are highly variable and depend largely on water chemistry rather than the level of treatment. The presence of dissolved salts, organic matter, and pH variations significantly influences cement hydration kinetics, phase development, and microstructural evolution, resulting in inconsistent mechanical behavior across studies. Analysis of hydration mechanisms confirms that conventional models do not fully capture the complexity introduced by secondary-treated domestic wastewater. External chemical inputs modify key processes such as C–S–H formation, AFt/AFm equilibrium, and long-term densification, underscoring the need to reinterpret classical hydration frameworks under secondary-treated domestic wastewater conditions. Similarly, a review of standards reveals that existing regulations (e.g., ASTM, ACI, BS, IS) have limited applicability because they rely on simplified chemical thresholds or potable water equivalence and do not consider synergistic interactions among contaminants. Consequently, performance-based evaluation criteria are essential to ensure reliable concrete performance. From a mechanical perspective, the literature shows that while reductions in compressive and flexural strength are frequently reported, improvements or negligible effects are also possible when the secondary-treated domestic wastewater chemical composition is favorable. This variability underscores the need for case-specific evaluations rather than generalized assumptions. Furthermore, advances in experimental methodologies—such as SEM, XRD, MIP, and durability testing—have improved our understanding of microstructural and long-term performance, enabling more robust assessments. Future research should adopt an integrated, multiparametric approach that combines water chemistry, hydration mechanisms, and mechanical performance. In this context, incorporating reinforcement strategies, such as steel fibers (including recycled alternatives), is a promising approach to mitigate potential performance losses, improve crack control, and enhance durability. Furthermore, more research is needed on durability-related aspects such as corrosion, permeability, and long-term stability. In general, the use of secondary-treated domestic wastewater in concrete should not be evaluated solely on compliance with standard limits or treatment classification, but rather through a comprehensive framework that integrates chemical characterization, experimental validation, and performance-based design. This approach is essential for promoting sustainable construction practices while ensuring the reliability and durability of concrete materials.

5. ACKNOWLEDGEMENTS

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