

Review Article

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Applications of micro-nanobubble and its influence on concrete properties: An in-depth review

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Abstract: Micro-nanobubbles (MNBs) are tiny bubbles of water used in various industries. The production methods and properties of concrete containing MNBs and the applications of MNBs in different industries are reviewed. Then, the effect of MNBs on the properties of fresh and hardened concrete is described. Next, we assessed the advantages and disadvantages of using MNBs in different types of concretes, environmental and economic impact, and research gaps in the concrete containing MNBs. Even though the presence of MNBs in concrete has an undesirable effect on workability and rheology parameters, the results of workability are in the range of the European Guideline for Self-compacting Concrete regulations and the British Standard for conventional concrete. In contrast, using sulfoaluminate cement instead of Portland cement and MNBs in concrete improves rheological characteristics. The review also shows that MNBs improve the mechanical properties of concrete by up to 31% for compressive strength, 10–20% for tensile, and 3–34% for flexural strength. Furthermore, concrete containing MNBs has performed better than conventional concrete in terms of durability properties such as electrical resistivity, ultrasonic pulse velocity, chloride penetration resistance, and resistance to freezing–thawing cycles (F-T cycle). MNBs in concrete reduce the porosity by 17% and decrease the size of the holes. Water absorption of MNB concrete at 28 days decreased by 20%, and chloride permeability

reduced by 20%. MNBs in concrete help to develop the resistance of cement-based materials improve the elastic modulus at early ages and increase the ability to resist cracking, which can reduce the crack width. Still, it is necessary to carry out more experimental work for workability and durability, especially for SCC. Even though a few studies indicate a slight impact on the environment, environmental and economic effects, and production challenges need more investigations.

Keywords: micro-nanobubble, workability, durability, mechanical properties, heat of hydration, environmental pollution, economic evaluation

1 Introduction

Nanotechnology has been considered a pivotal technology in recent years, and today, countries around the world are trying to be leaders in the development of science and technology and offer solutions for various social and economic problems. Nanotechnology is focused on as a core technology that can solve global energy resource and demand issues and can contribute to economic goals such as overcoming productivity loss, creating industry convergence, and increasing employment. Therefore, many countries are making huge investments in the development of nanotechnology at the national level [1]. One of the nanotechnology methods that has recently received attention is micro-nanobubble (MNB)-based water methods. Microbubble has one of the physical and chemical properties that are used in water treatment [2–5]. Micro-nanobubbles of water have various applications in wastewater treatment. The processes of aeration, disinfection, flotation, and advanced oxidation are the most commonly used methods in wastewater treatment that utilize micro-nanobubble technology. Studies have shown that using micro-nanobubble technology in wastewater treatment can increase the efficiency of pollutant removal, reduce the size of facilities, shorten operation times, and lower the cost of operation and maintenance in water treatment plants [3].

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In recent years, the use of nano-scale additives, such as nano-silica, nano-alumina, nano-titanium, and nano-carbon tubes, has become very common in conventional concrete to improve its mechanical characteristics [6]. They are used to improve the mechanical properties and durability parameters of concrete due to the problems of being expensive, inaccessibility, and transportation issues, and because the particles of these materials are very hard, fine, and round due to their nano dimensions, they have negative environmental and health impact and are very dangerous for human health.

Recently, a new micro-nano additive called micro-nanobubble water (MNBW) has been used in the production of mortar and concrete in addition to being used in the water and wastewater industry. These MNB structures are water-to-bubble additives that do not add a new chemical composition to concrete [7,8]. Among nanomaterials, MNBs can be used as a supplement or a substitute for water used in concrete [9]. Nanobubbles are an important topic in the industry. Various companies in Canada, Japan, South Korea, the United States, and others have claimed to have produced nanobubbles with unique methods [10].

Given that the mechanical strength and durability of different types of concretes significantly impact their lifespan and that large amounts of concretes are used in constructing various buildings worldwide, enhancing mechanical strength and durability using MNBW in concrete can reduce resource consumption. By increasing the lifespan of concrete, this approach supports environmental sustainability. This article reviews the use of MNBW across various industries and examines its effects on the workability, mechanical strength, and durability of different types of concretes. In addition, it discusses further research proposals concerning the environmental and economic impacts, production challenges, and the overall impact of using MNBW.

2 Introduction of MNBs

MNBs are small bubbles. Their diameter is 1–100 μm and less than 1 μm (these numbers may vary differently in previous studies [11,12]) and have been studied for various applications. Figure 1 shows the main differences between large bubbles, microbubbles (MBs), and nanobubbles (NBs). In MBs, the bubble size gradually decreases and then collapses due to long-term stagnation and dissolution of internal gases in the surrounding water, while NBs remain stable for months and do not collapse suddenly. It has been found that the interface of NBs consists of tight hydrogen bonds, which in turn leads to the reduction of diffusion of NBs and

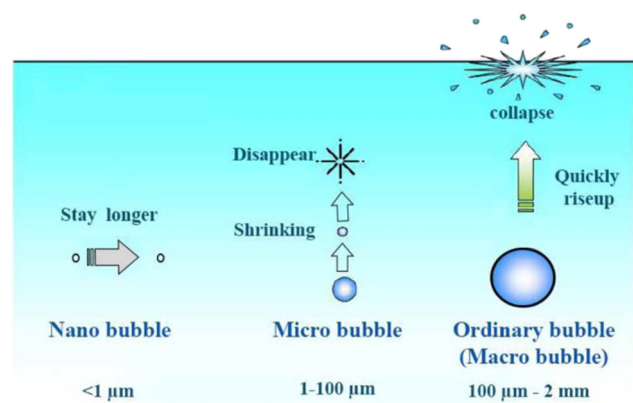


Figure 1: Difference between big bubble, micro bubble, and nano-bubble [5].

helps to maintain sufficient kinetic balance of NBs against high internal pressure [5,9,13,14].

However, small bubbles between these two diameters are usually called MNBs. Therefore, MNBs are very small cavities containing gas in an aqueous solution, which are formed by the aggregation of nanoparticles and molecules inside a protective layer. Researchers have noted that MNBs have the following six superior properties over conventional (or ordinary) bubbles [4].

- Large special area
- Longer stability in water
- High mass transfer efficiency
- Spontaneous production of free radicals
- MNBs can self-pressurize and dissolve in water
- The applications of MNBs in environmental pollution control have been widely considered

Production of MNBs can be produced in different ways. Before introducing specific methods, it is important to note that the demand for their production is largely application based, and validation of whether the products are gas bubbles is sometimes left out because of its game-changing potential. For scientific research on Bulk nanobubbles, it is vital to ensure this issue [15].

Extensive research has been done on the production methods of MBs and NBs, and different methods have been used for their production in different sources and for different uses. Although they have investigated the techniques or generators of MBs in their studies, most of the techniques or generators are such that by setting different working parameters, and they can also produce NBs, which are presented in Table 1 [11,16].

As outlined in Table 1, nanobubble production methods are categorized into four groups: flowing liquid usage, without accompanying liquid flow, by polymer, and low

Table 1: Classification of MNB production methods [16]

Num.	Category	Type
1	When flowing liquid is used	Spherical body in a flowing tube Rotary liquid flow type Static mixture type Venturi type Ejector type Multi-fluid mixture device Pressurized dissolution type
2	Without accompanying liquid flow	Rotary gas flow type Porous membrane type Electrolysis type Vapor condensation system Porous mullet ceramics technique
3	By polymer	Emulsion solvent vaporization Cross-linking polymerization Atomization and reconstitution
4	Low-power generation techniques	Flow focusing technique Microchannel technique Ultrasonic systems Micro-bubble technique Heating of carbon nanotube Laser induction breakdown in water Using organic membranes Shear flow in pipe and slits Generation of single MNB Fiber optic tips coated with nanoparticles

power generation techniques. Each category encompasses various types. For instance, within the “by polymer” category, three distinct methods are listed, with details provided in Table 1 for each method.

According to Harris *et al.* [11], the nanobubble production methods can be simplified into four categories based on their working principles: hydrodynamic method, acoustic method, mechanical agitation method, and electrochemical method. The hydrodynamic method operates on the principle of cavitation, while the acoustic and electrochemical methods utilize sound waves and electrolysis, respectively. The mechanical agitation method involves liquid stirring and bubble production, which depend on the speed of the mixer or homogenizer.

Another method for producing nanobubbles is the collapse production method, which involves the use of ultrasonic waves or shock waves to induce extreme pressure changes. To prevent bubbles from coalescing and disappearing, anticoagulant agents are often necessary. In certain cases, such as with rotary rotations or ultrasonic

waves, a rapid decrease in pressure to a level below the saturated vapor pressure causes the liquid to boil and disjoints the air, resulting in the separation of bubbles, though this process may also lead to bubble disintegration [17].

In the shearing production method, bubbles are generated through gas shearing within a turbulent flow in a gas–liquid mixture. This turbulence is often created using a tube venturi or by inducing rotating flow, such as shaking a bottle containing a mixture of gas and liquid. This method is effective in producing bubbles [17]. In the shearing production method, bubbles are generated through gas shearing within a turbulent flow in a gas–liquid mixture. Turbulence is induced by means such as a tube venturi or rotating flow, including the agitation caused by shaking a bottle containing a gas–liquid mixture, all falling under this category. In the pressurized dissolution production method, gas is dissolved into the liquid under the pressure of a compressor. Once the liquid reaches supersaturation, the pressure in the tank is rapidly released, returning the liquid to normal pressure. This sudden change separates the super-saturated gas, resulting in bubble formation [17]. Microporous production method: Bubbles are generated as pressurized gas flows through porous materials such as glass or metal plates with micro-scale open pores, allowing free connection with the fluid. Alternatively, a small-diameter expanded glass tube submerged in the liquid can also produce bubbles. Solid trapping production method: Bubbles form when gas becomes trapped in ice or solid particles dissolve in a liquid.

Chemical reactions production method: Molecular nanobubbles (MNBs) are generated as a result of some of the gas produced at an electrolysis electrode undergoing transformation [17].

Generally, cavitation is defined as the formation of small bubbles that are filled with gas or vapor or a combination of both, and the subsequent activities are growth, disintegration, and return to the original state in liquids. Depending on the gas forming the bubble, cavitation can be divided into two categories: vapor and gas (Table 2) [18,19].

As depicted in Table 2, the cavitation mechanism for nanobubble production is categorized into two types: surface tension and energy storage. The surface tension method itself is further divided into two categories: hydrodynamic, which involves changes in liquid flow pressure due to system geometry, and acoustic, which relies on acoustic cavitation induced by ultrasound waves applied to liquids. To elaborate on the hydrodynamic method within the surface tension category, which operates based on changes in liquid flow pressure due to system geometry, a venturi tube can be utilized. This method has been applied in coal column flotation using a venturi tube to generate nanobubbles. For more

Table 2: Classification of cavitation mechanism [18,19]

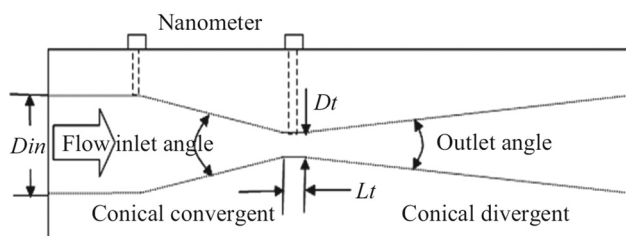
Num	Type	Category	Mechanism
1	Surface tension	Hydrodynamic method	Variation in the pressure of liquid flux due to system geometry
2		Acoustic method	Acoustic cavitation produced by applying ultrasound to liquids
3	Energy storage	Particle method	Passing high-intensity light photons in liquids
4		Optical method	Short-pulsed lasers focused into low absorption coefficient solutions

comprehensive information on the cavitation mechanism, readers are directed to previous studies [18,19]. Figure 2 illustrates a schematic diagram of the cavitation venturi tube, and Figure 3 shows a schematic diagram of a flotation column with a static mixer and a cavitation valve.

Figure 3 depicts a schematic representation of a 5.08 cm open floating column standing at a height of 250 cm, outfitted with a static mixer and an aeration tube designed for the production of pico-nanobubbles. The slurry feed is introduced into the feed tank, followed by the addition of an optimal quantity of collector and a foamer to prepare the mixture, facilitated by a ring and circulation pump [20]. Then the feed slurry enters the upper part of the flotation column. Air, fresh water, and recirculated tailings are sequentially mixed by a static mixer and a vent pipe before being injected into the bottom of the flotation column. The flotation column is also equipped with a washing water device, which is used to drain very fine mineral particles inside. A tailings discharge section has also been added to the floating column. This section is used to improve the mixing of bubbles and solids, and by recirculation, about a third of the solids have been added to the floating column. A static mixer is used to produce fine bubbles, and a static mixer is also used to improve the contact between bubbles and solids [20].

2.1 Stability

The stability of MNBs refers to their ability to maintain their shape, size, and properties over time. Several factors

**Figure 2:** Schematic diagram of cavitation venturi tube [20].

influence the stability and reactivity of NBs, including bubble size and characteristics, zeta potential, and surface properties. In addition, the properties of NBs are influenced by the solution's characteristics, the type of gas used, and the energy inputted into the system for nano-bubble production. Solution properties such as temperature, pressure, ion type, ion concentration, pH, presence of organic substances or impurities, presence of surfactants (surface activators), and the concentration of saturated gas have a significant impact on the characteristics of NBs. Moreover, the specific gas employed and its solubility and reactivity can also affect the bubble's properties [18,21–23].

2.2 Characteristics of MNBs and their controlling factors

2.2.1 Bubble size

The size of air bubbles is the most important characteristic associated with them. Generally, MBs are bubbling whose diameter is about micrometers, but in studies, their diameter ranges are different. Bubbles can be classified into macro bubbles, MBs, sub-micron bubbles, or NBs corresponding to ordinary or big bubbles, and fine and ultrafine bubbles based on their size [11,16].

Macro bubbles are larger and more influenced by buoyancy and speed, which makes them prone to instability during measurement. On the other hand, longer stability time in liquid makes MNB characterization more feasible. It is worth noting that the size of the bubbles is dynamic and by merging or shrinking, the bubbles can transform into each other [11,24]. In Figure 4, the size distribution of MNBW bubbles is depicted based on three measured parameters: volume, number, and intensity.

The size dispersion of MNBs was assessed using the nanoparticle size analyzer tool on specimens aged 1 day, employing the cumulant analysis method that considers three parameters: volume, number, and intensity of specimens. This analysis was conducted at the central laboratory of Ferdowsi University of Mashhad in Iran. Figure 4a–c

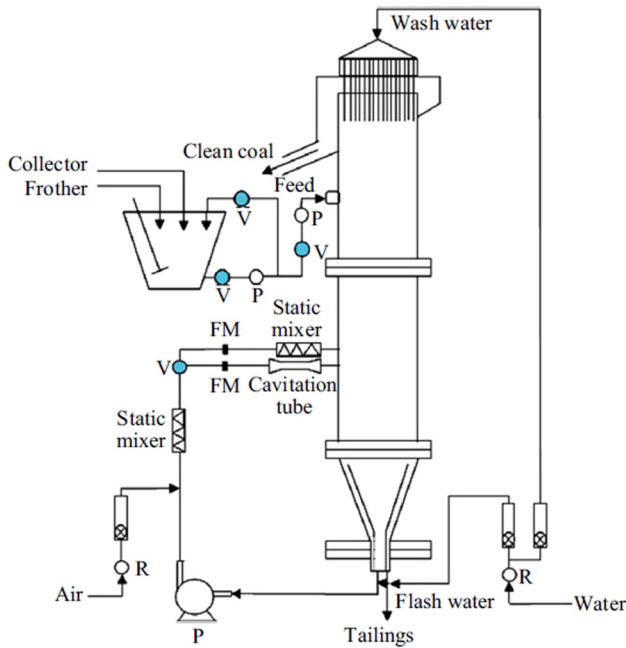


Figure 3: A schematic diagram of a flotation column featuring a static mixer and a cavitation valve [20].

depicts the size dispersion of MNBs based on volume, number, and intensity parameters, respectively [25].

2.2.2 Mass transfer efficiency

Mass transfer refers to the overall transfer of mass from one place to another, which is created due to the presence of a specific driving force in the system. The mass transfer process involves various phenomena. One of these is the free diffusion of molecules, which occurs in a laminar fluid and static medium. This refers to the movement of molecules from an area of high concentration to an area of low concentration, driven by random molecular motion. Another phenomenon is mixing and eddy diffusion, which occurs in turbulent fluid. Finally, the mass transfer also includes the transfer of mass between gas and liquid phases. This phenomenon is often seen in processes like absorption or stripping. These different phenomena play an important role in various industrial processes and natural phenomena, contributing to the overall understanding of mass transport [11].

2.2.3 Bubble rising velocity

Bubble's behavior in liquid solutions is greatly influenced by a parameter called the rate of increase. The physical

characteristics of the liquid play a significant role in determining the growth rate of MBs. MBs have a very low Reynolds number (approximately $Re \leq 1$) because of their small size. As a result, these bubbles behave similarly to spherical bubbles and occasionally resemble solid spheres, where the gas-liquid boundary allows for free flow. The upward velocity of an MNB moving through a liquid is determined by the balance between buoyancy and drag forces acting upon it. The growth rate can be mathematically described using Stokes' law. Hadamard and Rybczynski developed the Stokes theory to explain the behavior of liquid bubbles or droplets [11,16,26,27].

$$U = \frac{\rho_l g D_b^2}{18\mu},$$

where ρ_l is the density, D_b is the bubble diameter, μ is the water viscosity, U is the rate of increase, and g is the gravitational constant.

2.2.4 Zeta potential

Zeta potential is a physical property possessed by every particle in a suspension, and it can be utilized to enhance and optimize the creation of suspensions and emulsions [16]. Zeta potential refers to the electric potential difference between the moving scattering medium and the static layer attached to the scattering particle. The value of zeta potential is strongly influenced by the stability of emulsions or colloids, in both the short term and the long term [11]. In the case of MNBs, their zeta potential describes their charge characteristics, which impact their dispersion behavior. In the case of MNBs, their zeta potential describes their charge properties, which have an impact on the dispersion behavior of particles. High absolute values of zeta potential are suitable for improving MNB stability. When particles possess a high negative potential, they typically exhibit a mutual repulsion. Conversely, particles with low zeta potential lack the necessary force to prevent them from approaching each other [28]. Many factors affect the zeta potential of bubbles, such as solution pH, gas, ionic strength, additive concentration, and temperature. Generally, increasing the pH will decrease the zeta potential [29]. The zeta potential of NBs is influenced by the gas's ability to generate hydroxyl ions on the bubble's surface. Solutions with high pH, low temperature, and low salt concentration promote a high negative zeta potential for bubbles. In long-term experiments, the zeta potential of bubbles tends to diminish as the bubble size increases [18]. In Zhang *et al.*'s research [30], a correlation between the zeta potential of NBs and their size has been identified, indicating a special

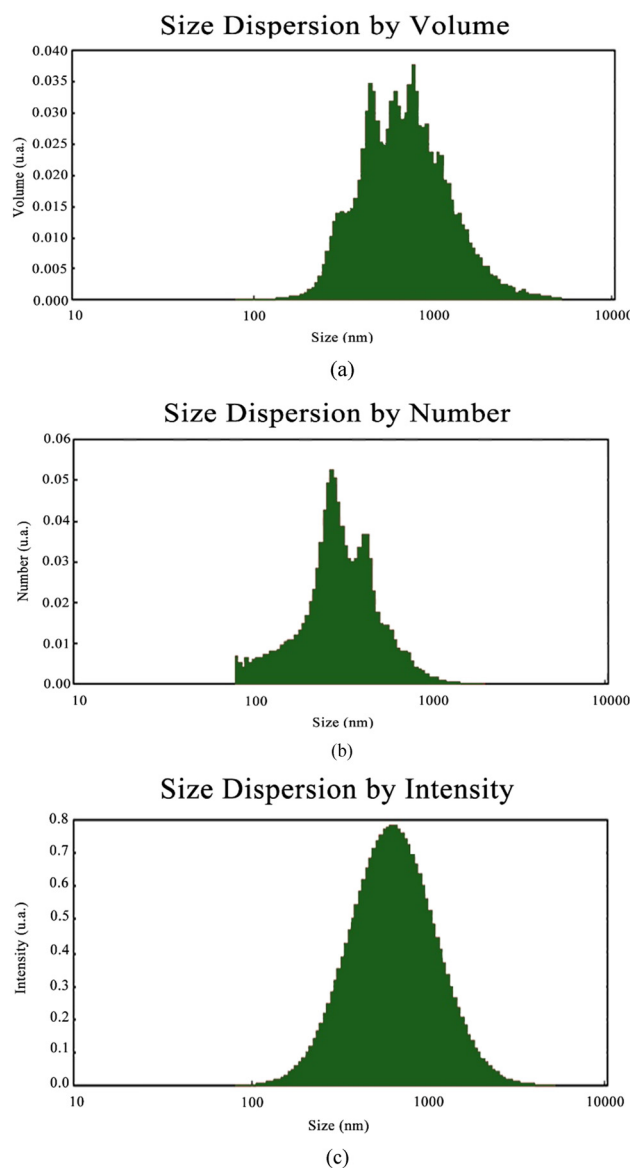


Figure 4: The air bubble size distributions of MNBs in water [25]. (a) Air bubble size distribution in MNBs by volume, (b) air bubble size distribution in MNBs by number, and (c) air bubble size distribution in MNBs by intensity.

relationship (Figure 5). It is a graph that shows the changes in zeta potential for water containing MNBs at the age of 1 day.

Zeta potential stands out as a pivotal parameter of MNBs, playing a crucial role in predicting the stability of particles within the solvent. The surface zeta potential of water containing MNBs is assessed using the zeta compact cad instrument. Figure 5 demonstrates the variations in zeta potential of water containing MNBs at the age of 1 day, spanning from -10 to -40 mV experimented at the central laboratory of Ferdowsi University of Mashhad in Iran [25].

2.2.5 Hydroxyl radical

Generally, as bubbles smaller than $10\ \mu\text{m}$ continue to shrink, the electric charge density of the double layer experiences a rapid increase. When a bubble bursts in an aqueous solution, the highly concentrated positive and negative charges rapidly release the accumulated energy, resulting in the production of numerous free radical ions, including oxygen ions, hydrogen ions, and hydroxide ions. The hydroxyl radical, in particular, exhibits strong oxidation properties, enabling it to oxidize and decompose challenging-to-decompose organic pollutants like phenol. This makes it highly effective for water treatment purposes. MNBs are capable of generating free radicals without requiring any external stimuli or additive agents. However, it is important to note that these free radicals have a short lifespan. Numerous studies have been conducted to investigate the effect of free radicals in water treatment. Experimental findings indicate that the hydroxyl radical can serve as the primary active oxidant species (accounting for 82% of the total) in the decomposition of butylated hydroxytoluene by ozone MNBs [31–34].

2.2.6 Rheological behavior

Rheology is the scientific field that investigates how matter deforms and flows when subjected to external forces. It can be categorized into two branches: surface rheology and bulk rheology. In measuring the rheological properties of a material, it is important to know the flow properties such as shear stresses and shear rates. The relationship between shear stress and shear rate is shown graphically in a flow curve. Fluids can be identified by their flow curves. Various models – or constitutive equations – have been developed to idealize flow curves. Six of the most common constitutive relationships associated with concrete are shown in Figure 6 [35].

The yield stress and plastic viscosity are the two primary parameters measured by rheometers when applying the Bingham model. Equation (1) presents the rheological equation that defines the Bingham model [9].

$$\tau = \tau_0 + \mu \cdot \dot{\gamma} \quad \tau \geq \tau_0, \quad (1)$$

where τ is the shear stress in Pa, τ_0 is the yield stress in Pa, μ is the plastic viscosity in Pa.s, and $\dot{\gamma}$ is the shear rate in $1/\text{s}$.

Some researchers have recommended the Herschel–Bulkley (H-B) model (equation (2)) to describe the shear thickening behavior of cementitious mixtures. In this model, the shear thickening behavior occurs when $n > 1$, and the shear thinning behavior occurs when $n < 1$. The value of n indicates the degree of shear thickening response.

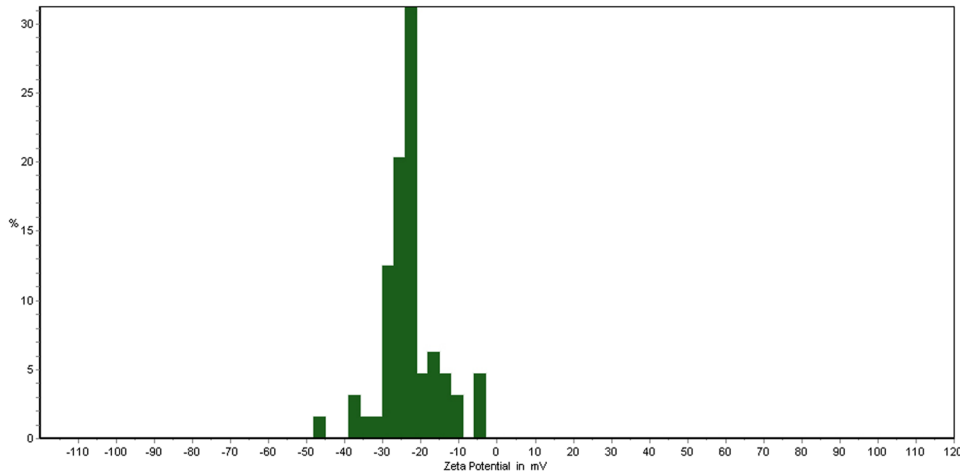


Figure 5: The variation of zeta potential for water containing MNBs at the age of 1 day [25].

$$\tau = \tau_0 + k \cdot \dot{\gamma}^n \quad \tau \geq \tau_0,$$

where τ is the shear stress in Pa, τ_0 is the yield stress in Pa, and $\dot{\gamma}$ is the shear rate in 1/s. n is the flow index, and k is the consistency factor in Pa s^n .

Bingham's model was modified to describe the shear thickening and thinning behavior (equation (3)). In this regard, the shear thickening behavior occurs when $c/\mu > 0$, and the shear thinning behavior occurs when $c/\mu < 0$ [36].

$$\tau = \tau_0 + \mu \cdot \dot{\gamma} + C\dot{\gamma}^2 \quad \tau \geq \tau_0.$$

MNBs primarily due to bubble coalescence and coarsening are thermodynamically unstable systems. Previous research has demonstrated the significance of the rheological characteristics of the gas-liquid interface in determining the stability of MNBs [14]. In a study conducted by Shen *et al.* [37], the stability and rheological behavior of bubble suspensions coated with concentrated food emulsifiers were investigated. MBs were generated using flow concentration, where a food-grade emulsifier was employed. The emulsifier formed a thin shell around the MNBs, resulting in their stabilization. The diameter of the produced MBs ranged from 120 to 200 μm and could be controlled by adjusting the flow rate of the liquid and gas phases. To assess the rheological properties of the MBs suspension, a rotational rheometer was used. Gas retention in the experimental sample was determined through weight difference measurements. Shen *et al.* observed that MNBs remained stable over time without significant changes in size. Furthermore, it was discovered that as the shear stress increased, the viscosity of the system decreased. This observation suggests that the MNB suspension displayed viscoelastic properties. The reduction of static yield stress and plastic viscosity of SCC using MNB water were higher than tap water with the same amount of superplasticizer, concrete age, and

temperature [9]. Based on convexity in the diagram, shear thinning behavior was observed in concrete samples with MNBs. The c/μ (negative) ratio went up by increasing the superplasticizer dose. This means increasing the intensity of shear-thinning behavior by increasing the dosage and potential for segregation and bleeding [9].

3 Application of MNBs

MNBs find diverse applications across various fields, as depicted in Figure 7.

As shown in Figure 7, MNBs are utilized in drinking water and wastewater treatment, groundwater decontamination, and medical engineering, as well as in industrial sectors like agriculture, fisheries, and food. Table 3 presents an overview of some specific applications of MNBs.

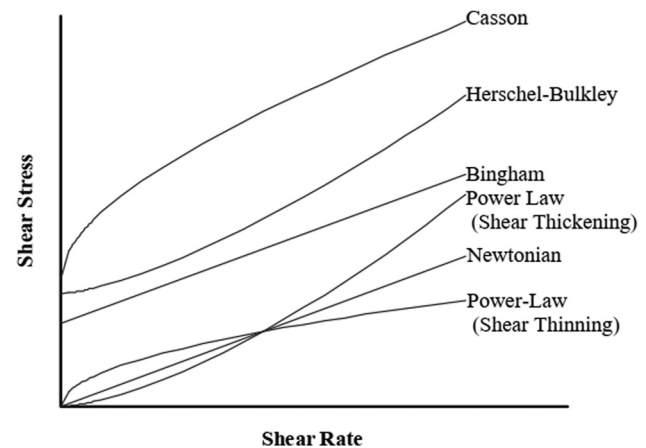


Figure 6: Six common models for determining the rheological behavior of concrete [35].

Table 3 shows the many applications of medical MNBs: medical, industry energy systems, sludge treatment, soil and groundwater remediation, waste water treatment, surface water purification, food industry, flotation, surface cleaning, and bacteria removal. In the medical field, MNBs are used to detect tumors in the human body with ultrasound imaging. They are also used to treat cancer. MNBs are used in genetics and are used to diagnose malaria. In the energy supply system of the industry, using MNBs, they remove oil and mixed carbon from water and bring economic benefits to water use. Also, MNBs are used in solar energy and are used to remove fine metal oxide particles. Also, in the presence of MNBs, the paint dries faster. In the food industry, MNBs are used to increase the yield and quality of the product by increasing the amount and time it stays in the soil. It also uses them to destroy microorganisms on the surface of fruits and vegetables.

4 Literature review of using MNBs in concrete

Nanotechnology, being interdisciplinary in nature, holds the potential to fundamentally transform the construction industry by interfacing with the science of concrete. In recent years, the use of nano-scale additives such as nano-silica, nano-alumina, nano-titanium, and nano-carbon tubes to conventional concrete to improve mechanical properties has been very common, but research on the effects of MNBs on concrete has been limited [7,9].

In the research, the effects of MNBs on fresh concrete and hardened concrete have been investigated to some extent. Literature survey indicates the results of various studies using MNBs in conventional concrete and self-compacting concrete (SCC).

4.1 Literature survey

This section presents the findings from a range of studies that have explored the use of MNBs in both conventional concrete and SCC.

Zhang *et al.* [76] studied the impact of MNBs on the rheology of concrete, focusing on bubble characteristics such as size, specific surface area, and distance factor. The research used 11 different types of air bubble agents and conducted gray correlation and classification analyses. Their findings suggest that bubble characteristics play a more important role in concrete rheology than air content alone. Smaller bubbles (10–200 μm) lead to a greater improvement in concrete slump and yield stress, as they distribute more evenly in the mortar, enhancing the balling and lubrication effect. Larger bubbles (beyond 200 μm) have less influence on cohesion. Classification analysis indicated that smaller bubbles (10–600 μm) result in greater slump increases compared to larger bubbles (1,600–600 μm). Overall, the research highlights the importance of bubble size and distribution in optimizing the rheological properties of fresh concrete. The presence of bubbles in the mortar improves the flow and rheological properties of fresh concrete by uniformly distributing small bubbles in the mortar. These



Figure 7: Applications of MNBs [38–45].

Table 3: Applications of MNBs

Field	Application	Ref.
Agriculture	Water treated with MNBs in agriculture improves the physiological and biological conditions of the soil by increasing aerobic microorganisms, which has a positive effect on plant growth	[32]
	NB water reduces CH ₄ diffusion and arsenic dissolution through oxidative modification of redox conditions in flooded soil	[46]
	MNBs accelerate metabolism in animal and plant species	[47]
	Using MNBs in hydroponic solutions to clean and sterilize irrigation water (ozone bubbles)	[32]
	The high oxygen content and permeability of MNBs cause plant root growth, shorten the growth cycle, and thus improve the economic yield	[48]
	The use of MNBs kills bacteria, removes harmful substances and odors from water, and improves the freshness and taste of fruits	[32]
	Removal of residual pesticides in vegetables	[49]
	MNBs are used for biological and weed control	[50–52]
	MNBW improves the seed germination rate	[53–55]
	MNBs improve blood flow and branchial respiration of fish	[50,54]
Aquaculture and fisheries	Application of treated MNBW to aquatic plants and fisheries significantly increases growth by improving nutrient uptake	[56]
Cellular biological	MNBs are used in fermentation	[57]
Energy and carbon neutrality	MNBs play an essential role in the production and use of hydrogen	[14,58]
	It was found that MNBs are a suitable option for increasing oil recovery	[14,59]
Medical	MNBs are used to detect tumors in the human body by ultrasound imaging	[60]
	MNBs are used to treat cancer patients in different forms and methods	[61]
	MNBs are used in the treatment of dentistry and conditions affecting the teeth and gums (placement, restoration, and extraction)	[62,63]
	MNBs are used in genetics	[64]
	MNBs are used to diagnose malaria	[65]
	MNBs remove mixed oil and carbon from water and provide economic benefits for water reuse	[66]
Industry energy systems	MNBs are used in solar energy.	[67]
	Removal of fine metal oxide particles	[68]
	To disinfect sediments using ultrasound waves with ozone MNBs	[69]
	In the presence of MNBs, the paint dries faster	[70]
Sludge treatment	MNB can significantly improve the quality of aquaculture water, which is mainly affected by aquaculture sludge	[4,71]
Soil and groundwater remediation	MNBs can greatly enhance bioremediation by accelerating the oxygen transfer process.	[4]
Wastewater treatment	The use of MNBs provides an environmentally friendly method for wastewater treatment through the formation of free radicals	[3]
	MNBs is a simple, efficient, low-cost, and environmentally friendly technology for removing oil pollutants and fine particles from wastewater	[4]
	The possibility of improving underground water using micro and ozone bubbles	[28]
	Removal of chlorinated organic compounds from wastewater	[72]
Surface water purification	MNBs produced from air and nitrogen can increase the activity of microorganisms and/or bacteria under anaerobic and aerobic conditions to accelerate the biodegradation of pollutants in water and sediment. As a result, through aeration with MNBs, water purification can be achieved more effectively.	[4]
Food industry	The breakdown of MNBs producing hydroxyl radicals can accelerate oxidative degradation.	[52]
	Increase in gas content in solution and retention time	[28]
	Increasing the yield and quality of the product by increasing the amount of oxygen and the retention time in the soil	[52,71]
	Killing microorganisms on the surfaces of fruits and vegetables	[52]
Flotation	MNBs are used to effectively improve the flotation efficiency of coal, phosphate, and sand chalcopyrite.	[14,73]
Surface cleaning	MNBs are environment-friendly surface cleaning agents	[14,74]
Bacteria removal	MNBs are effective in removing infectious pathogens in contaminated water	[75]

bubbles fill spaces between aggregates and cement particles, trapping free water and releasing it to form concrete lubrication. The introduction of bubbles thickens the mortar layer, increasing the distance between coarse aggregates, and reducing collision and frictional resistance, which significantly enhances concrete's overall performance.

Grzegorzczak-Frańczak *et al.* [77] examined the impact of using MNBs containing O_2 and O_3 gases in concrete. The study found that MNBs reduced concrete porosity, resulting in increased bulk and specific density, with a more pronounced effect from O_2 bubbles. Concretes with MNBs, particularly those with ozone, had lower water absorption and higher compressive strength at 14 and 28 days. After 150 freeze–thaw cycles, concrete with O_2 MNBs showed 44% less weight loss than the reference concrete, while O_3 MNBs demonstrated even less weight loss. The reduction in compressive strength was less for concretes with MNBs than for reference concrete. In addition, concretes with MNBs had higher thermal conductivity and lower total surface voids and apparent density, with the best performance seen in concretes with O_3 MNBs. Arefi *et al.* [78] investigated the effect of adding MNBs to water before mixing it with aggregate and cement. The results showed that concrete with MNBs had lower workability, with a slump about 10 mm less than conventional concrete. MNBs led to early or immediate hydration and lower temperature changes during setting. The setting time was reduced, and the 7- and 28-day compressive and tensile strength of concrete with MNBs were higher than those of conventional concrete.

Grzegorzczak-Frańczak *et al.* [79] studied the impact of MNBs of different gases (O_2 , O_3 , and CO_2) on the physical and mechanical properties of lime-cement mortars. They found that adding MNBs decreased the workability of fresh mortar, especially with CO_2 MNBs. Higher replacement percentages of MNBs also led to a greater decrease in workability. Concretes with 100% MNB replacement had higher specific densities and turbidity than those with 50% replacement. Volumetric density increased with CO_2 but decreased with O_2 and O_3 MNBs. The highest compressive strength after 28 days was achieved with the 50% O_2 mortar, showing a 31% improvement compared to the reference sample. Flexural strength generally increased in most mortars after 56 days, ranging from 8.3 to 34% higher than the reference sample, except for a 2.6% decrease in the 50% O_3 mortar.

Asadollahfardi *et al.* [80] replaced drinking water with MNBs and metakaolin as mineral substitutes in concrete. This change accelerated the hydration process and increased the 28-day compressive strength by 8.82 and 13.2% for 50 and 100% MNB replacements, respectively, although these gains were slightly reduced over 90 days. Tensile strength also improved by 10–19% with MNBs, while 42-day flexural

strength rose by 3.97 and 5.7%. Water absorption was significantly reduced at 28 days and continued to decrease slightly at 90 days. The 28-day rapid chloride permeation test (RCPT) showed that 50% MNB replacement greatly reduced chloride penetration, with a slight increase at 90 days. Replacing water with MNBs also increased the concrete's electrical resistance. Mohsen Zadeh *et al.* [81] investigated the impact of using pozzolans and MNBW in concrete mixtures. Replacing 50% and 100% of water with MNBs increased the 28-day and 90-day compressive strength. The 28-day tensile strength increased by 10 and 19.6% for 50 and 100% MNBs, respectively, while the 42-day flexural strength increased by 2.85 and 5.48% with 50 and 100% replacements. Water absorption decreased significantly at 28 days with reductions of 16 and 20% for 50 and 100% MNBs, respectively, and continued to decrease slightly at 90 days. Chloride permeability also reduced significantly at 28 and 90 days with 50 and 100% MNBs. In addition, MNBs reduced the pH of concrete.

Yahyaei *et al.* [9] studied the impact of MNBs on SCC. They found that adding MNBs slightly reduced slump flow and increased V funnel time, leading to faster slumping. MNBs also improved permeability and increased the J-Ring test value, but had a little effect on L-box and air percentage results. MNBs enhanced compressive strength but reduced it in mixtures with silica fume. MNBs improved concrete's impermeability and specific electrical resistance. SEM results showed well-distributed MNB particles under 10 μm . MNB size under 50 nm affected shrinkage but not compressive strength. Kim *et al.* [82] conducted research in which they used water containing high concentrations of hydrogen nanobubbles as mixing water for cement mortar. They explored the effects of substituting regular mixing water with hydrogen nanobubble water (HNBW) in proportions of 40 and 80%. The nanobubbles used in the study had diameters of less than 200 nm.

TGA is the most widely used method to determine the degree of hydration. In this research, according to Bhatti's method [76], temperature ranges and types of hydrations were determined. This approach identifies cement hydrates by measuring the weight loss that occurs over a specific temperature range. They concluded that the flexural strength of cement mortar increases with the replacement of nanobubbles. As the amount of substitution increases, the bending strength also increases. Nanobubble has not had a significant effect on the compressive strength of mortar for 3 and 7 days. While the 28-day compressive strength has increased by 6.5 and 11% for 40 and 80% replacement, respectively. Furthermore, by comparing the XRD patterns of cement paste, the pastes made with 0, 40, and 80% substitution of hydrogen nanobubbles had similar patterns.

With increasing nanobubble concentration, although there was no difference in the type of crystalline phase, a slight difference in the peak intensity of scattered X-rays was observed. As a result, it was confirmed that the new crystalline phase was not formed by the nanobubbles. In addition, it was confirmed that the reaction speed of nanobubbles with cement particles affects the improvement of mortar strength. Moreover, TGA test results show that:

- During initial heating (28–105°C), the weight loss of all samples was similar.
- As the concentration of bubbles increased during heating up to 1,000°C, the weight loss increased gradually.
- In each temperature range, a sudden change in the “weight-loss-time” curve occurs.
- The amount of total hydrate of cement (C–S–H, $\text{Ca}(\text{OH})_2$, CaCO_3) increases with the increasing concentration of hydrogen nanobubbles. The increase of CaCO_3 for 40 and 80% substitution is almost similar, and the increase in the other two hydrates causes a difference for these two substitution percentages.
- With the increase in the concentration of nanobubbles, the increase in C–S–H is greater, and this means that according to the bubble concentration,
- C–S–H ($3\text{CaO}\cdot\text{SiO}_2\cdot 3\text{H}_2\text{O}$) developed more actively than $\text{CH}(\text{Ca}(\text{OH})_2)$.
- The hydration and pozzolanic reactions are continuously promoted by hydrogen nanobubbles, leading to an overall increase in the degree of hydration, which, in turn, improves the mechanical strength of the cement mortar.
- Increasing nanobubble concentration increased the formation of Ettringite and C–S–H crystals at the same treatment dose.

Wan and He [83] investigated the impact of MNBs and an aluminum sulfate nonalkaline accelerator on the volumetric stability of cement-based materials (shotcrete) over 180 days. The addition of MNBW significantly reduced shrinkage deformation, including self-shrinkage and drying shrinkage, by over 10% in 28 days and about 6.5% in 180 days. MNBW improved internal moisture, reduced porosity by 16.9%, and decreased average pore size by 22.9%, increasing density. MNBs also lowered surface tension and negative capillary pressure, reducing the risk of shrinkage and cracking. MNBW enhanced early resistance development and improved elastic modulus, minimizing the crack width and increasing the ability to resist cracking.

Sheikh Hassani *et al.* [25] examined the effects of using water with MNBs on cement mortar and concrete at different ages and water-to-cement (W/C) ratios. MNBW slightly increased concrete temperature and pH while boosting water's electrical conductivity and turbidity. It also shortened the

initial and final setting times of cement pastes. MNBW reduced the flowability of cement mortar by 18.75% and decreased slump by 50%. MNB concrete showed lower slump loss over time and increased compressive strength by 16% at 7 days and 7% at 28 days. MNBs enhanced early hydration product formation, leading to less strength increase beyond 28 days. Scanning electron microscopy revealed well-formed crystals and dense solid masses with fewer micropores in MNB concrete.

Lan *et al.* [84] studied the impact of water-containing nanobubbles and nano silica on air content, freeze–thaw resistance, and hydration in cement materials at different air pressures (0.4, 0.7, and 1 atmosphere). They used analytical techniques like SEM, XRD, and TG-DSC to evaluate hardened cement paste samples. All nanobubbles were smaller than 90 nm, with an average size of 45 nm. Nanobubbles increased the solidified air content in cement paste by 12.3–22% across different pressures, reduced the distance factor, and varied cavity diameter and density depending on pressure. Nanobubble water accelerated cement hydration, increasing calcium silicate hydrate and other cement hydration products. SEM examination showed smoother, more compact pore walls in cement paste with nanobubble water. Compressive strength increased by 0.3–3.9% based on air pressure. Although low pressure increased weight loss, especially after 50 freeze–thaw cycles, nanobubble water improved the freeze–thaw resistance of air-bubbled and nonbubbled samples at low pressure.

Kim *et al.* [85] investigated the impact of using hydrogen nanobubbles with high concentrations on the performance, durability, water tightness, and microstructure of cement mixtures. By using osmosis for 40 and 80 min, they increased the concentration of hydrogen nanobubbles in water, resulting in more stable states and particle sizes decreasing with longer osmosis time. This increased concentration of nanobubbles led to higher compressive strength, especially after 7 days, though it reduced workability. The higher nanobubble concentration also decreased porosity and increased the density of the mortar, forming a denser cavity structure. The results showed changes in pore distribution that supported a solid structure in the cement paste. SEM tests revealed that as HNBW concentration increased, the internal structure of the cement paste became denser, with more hydration reactions like ettringite and C–S–H crystal formation. Khoshroo *et al.* [86] studied the impact of replacing traditional concrete with MNBs at 30, 60, and 100% levels on concrete properties. They found that MNB concrete reduces fluidity due to accelerated hydration but can be managed by adding a superplasticizer. MNB concrete has higher density and packing, with higher replacement percentages leading to greater packing. Compressive strength increased by 6, 9, and 13% at 28 days for 30, 60, and 100% replacement levels, respectively, due to faster

hydration and improved homogeneity from particle bubbles. However, a decrease in compressive strength was seen at 90 days likely because most hydration occurred within the first 28 days.

Tayebi Jebeli *et al.* [87] studied the enhancement potential of using MNBW as a replacement for waste foundry sand (WFS) in concrete mixtures. They replaced natural sand with varying levels of WFS (10–40%) and MNBW (50–100%) in concrete mixtures. The optimal mixture was found to be 40% WFS concrete containing 100% MNBW. Adding WFS reduced slump compared to a reference sample, especially with MNBW. The sample with 20% WFS showed the highest increase in compressive strength across different time points, but higher levels of WFS replacement led to decreased compressive strength. In general, MNBW improved compressive strength, particularly at 90 days. Ultrasonic pulse velocity (UPV) results showed no significant effect on concrete quality with MNBW, although water absorption decreased slightly up to 20% WFS replacement. The study found improved chloride penetration up to 20% WFS replacement, with no significant changes beyond this point. SEM tests indicated a reduction in the number and size of pores with WFS, but cracks on the surface increased in width with higher WFS levels and in mixtures with MNBW.

Lee *et al.* [88] explored the impact of using nanobubble water in cement composites, including high-performance concrete, lightweight cement composites, and high-strength mortar. The water used contained 7% nanobubbles with an average size of 750 nm. Results showed that using nanobubble water improved the compressive strength of cement composites compared to those made with regular water, even with a lower cement ratio. The performance improvement ranged from 3 to 22%, with the greatest increase (22%) seen in ultra-high-performance concrete (UHPC). The study also found that nanobubble water enhanced the workability of the concrete, especially in UHPC, and attributed the improvement to the small size and high quantity of the nanobubbles, which interact with silica fume and prevent the ball effect. Larger nanobubbles, in contrast, tend to float up and disappear from the mixing water. He *et al.* [89] studied the effects of MNBs and mineral additives on the performance, durability, and mechanical properties of C60 concrete. They found that while MNBs decreased the workability of both conventional concrete and self-consolidating concrete (SCC), samples containing MNBW and silica fume exhibited about 4% higher compressive strength. In addition, the penetration depth of carbonation in samples with MNBs decreased by about 38%. Frost resistance tests showed a 53% reduction in mass loss and a 2.9% decrease in the loss of dynamic elastic modulus during ice melting cycles, indicating that MNBs

improve the durability and mechanical properties of C60 concrete.

Wan *et al.* [90] explored the cold resistance of shotcrete concrete with additives and MNBW. They found that using MNBW reduced the size of concrete pores, increased density, and improved bonding between paste and aggregate. MNBW enhanced the 28-day compressive strength of shotcrete concrete more with an alkaline accelerator than an alkali-free accelerator. MNBW also reduced the loss of compressive strength due to freezing and thawing, particularly after 200 cycles, where it reduced mass loss by 42.2% in concrete with alkaline accelerators and 5.4% without. In addition, samples with normal water showed serious damage after 200 cycles, whereas those with MNBW maintained their relative dynamic elastic modulus. Overall, MNBW improved cold resistance and durability in shotcrete concrete.

Chang *et al.* [91] used MNBW in the mixing process of sulfo-aluminate cement (SAC) paste and found that MNBW enhanced hydration and improved the microstructure of the cement matrix. SAC paste mixed with MNBW showed improved mechanical properties compared to paste mixed with tap water. Compressive strength increased by 23.8% at 1 day and 14.4% at 28 days, while flexural strength increased by 16.6% at 1 day and 10.7% at 28 days. MNBW also reduced the setting time of the cement paste and lowered its plastic viscosity. MNBW facilitated earlier and higher heat release during hydration, and SEM images revealed a more uniform distribution of hydration products and fewer cracks. MNBW samples had smaller potential pore sizes and lower porosity, resulting in a denser cement matrix. The study presents a unique method for improving the performance of SAC-based materials, which can benefit various construction projects.

Chen *et al.* [92] examined the impact of using hydrogen MNBs on the workability and mechanical properties of concrete. The study found that adding nanobubble water improved the flowability and slump of concrete, particularly with higher water-to-cement (W/C) ratios. Concrete samples with nanobubble water exhibited increased compressive strength, particularly at 3 days (18%), and showed improvements in water absorption, electrical resistance, and chloride penetration resistance across different ages. SEM images revealed higher hydration rates and formation of hydration products in mixtures containing nanobubble water, indicating enhanced performance due to fewer pores and greater density in the concrete.

Yahyaee *et al.* [9] evaluated the effect of using micro-nanobubbles on the rheology of SCC. The results of their study have shown that the plastic viscosity and yield stress were higher in samples made with MNBs. In concrete containing MNBs, shear thinning behavior has occurred and

the c/μ ratio (negative) has increased with increasing amount of superplasticizer. When the dosage of superlubricant increased from 4 to 5.5 kg/m³, the use of MNBs increased the percentage of air in SCC by 10, 5, and 4.76%.

Chen *et al.* [92] investigated the effects of using 150 nm HNBW in cement concrete. They found that HNBW enhanced workability and mechanical properties of concrete while maintaining compressive strength even when cement content was reduced by 10%. HNBW also improved concrete durability, including better water absorption, electrical resistance, and chloride permeability resistance. SEM imaging confirmed the improved quality of concrete with HNBW. The increased workability was attributed to the adsorption of negatively charged hydrogen nanobubbles on cement particles, leading to dispersion and cushioning. HNBW can reduce the need for cement and additives, improving sustainability. The improved mechanical properties and durability result from the weak alkalinity of HNBW and the generation of hydroxyl radicals, which promote cement hydration, compaction, and reduced internal pores.

Tochahi *et al.* [93] studied the mechanical properties and durability of concrete samples with natural meta-kaolin and zeolite pozzolans mixed with water nanobubbles. The samples were cured in both seawater and standard conditions. At 28 days, the sample with 100% MNBs cured in seawater showed improvements compared to the same mixture cured in standard conditions. Specifically, it exhibited increased compressive strength (6.97%), tensile strength (12.82%), bending strength (11%), and electrical resistance (14%). In addition, it showed reductions in water absorption within 30 min (10.8%) and RCPT results (10.21%).

Considering the mentioned literature reviews, MNBs improve the mechanical properties of conventional and SCC. Up to 31% improvement has been reported for the compressive strength of concrete containing MNBs. The tensile and flexural strength of MNB concrete also improves between 10–20 and 3–34%, respectively. Concrete containing MNBs also affects the durability properties, so the porosity of concrete decreased by 17%, and the size of the voids also decreased. The 28-day water absorption of MNB concrete decreased by 20%, and chloride permeability also reduced significantly; this reduction has been reported in some sources up to 67%. The presence of MNBs in concrete increases the freeze–thaw resistance of concrete. Lan *et al.* [84] indicated that both NBW and NS can improve freeze–thaw resistance and mechanical strength of samples at low atmospheric pressure by accelerating cement. They proved that NBWs and nano-silica can improve freeze–thaw resistance and mechanical strength of samples at low cement hydration. Finally, MNB concrete may be suitable for shotcrete [90] because it reaches acceptable compressive strength sooner than conventional concrete.

The presence of MNBs in concrete has a negative effect on workability and rheology parameters. Their presence reduces the slump flow by 5–10%. Also, the J-ring height difference and V-Funnel time experienced a slight increase in SCC. In the investigation of researchers, MNBs have no noticeable effect on the L-Box ratio. However, the workability of SCC using MNBs is in the range of European Guidelines for Self-Compacting Concrete (EFNARC) [94] (2005) guidelines for SCC production.

It is necessary to find types of workability, mechanical, and durability experiments of MNB concrete that have been performed in the world to determine the gap in research. Considering research reported in Table 4 indicates types of experimental works associated with the workability, mechanical, and durability of MNBs that have been done up to now.

Table 4 shows the effect of adding MNBs on the performance of conventional concrete and SCC and divides the effect of adding MNBs on performance into efficiency, mechanical properties, durability, etc. To evaluate the workability of concrete, slump flow, J-ring rate, T₅₀, V-funnel time, L-box ratio, U-box ratio, visual stability index (VSI), air content, static segregation, dynamic segregation is used. The third column of Table 4 indicates various workability, mechanical and durability tests to evaluate the efficiency of concrete containing MNBs are listed to evaluate the mechanical properties, compression strength, flexural strength, tensile strength tests have been used in previous studies. To evaluate the durability of concrete containing MNBs, water absorption (volumetric), SEM, RCPT, electrical resistance, resistance to the freeze–thaw cycle, resistance to water penetration, UPV, resistance to water penetration, resistance to chloride penetration (RCMT), carbonation depth, and impermeability tests have been used more.

According to the British standards (BS) (2019) [95], there are four classes for the slump of conventional concrete, including S1, S2, S3, and S4, which depend on the type of application of concrete (Table 5). In addition, it is possible to use a mixture of drinking water and MNBs in the preparation of concrete, which caused an increase in slump compared to the use of only MNBs. Finally, if sufflaminate cement (SAC) is used for MNB concrete, improves the rheological properties of SAC paste [91] and environmental impact compared to using Portland cement. Kanyenze *et al.* [96] reached contradicting slump outcomes compared to the work of Arefi *et al.* [78] that they indicated an important reduction in flowability (or consistency). They claimed the difference in outcomes can be attributed to the consumption of MNB water compared to pure nanobubble water in this test, which resulted in different water characteristics and the following impacts on concrete.

Table 4: Types of tests performed for MNB concrete

Properties	Concrete type	Test	Ref.
Workability	Conventional	Slump	[25,76,78,79,82,86–89,92]
		Initial setting time	[9,25,78]
		Final setting time	[9,25,78]
	SCC	Slump flow	[9]
		T ₅₀	
		J-ring rate	[9]
		V-funnel time	[9]
		L-box ratio	[9]
		U-box ratio	
		VSI	[9]
		Air content	[9,92]
		Static segregation	
		Dynamic segregation	
		Mechanical properties	Compression strength
Flexural strength	[9,77,79–81,85,91,93]		
Tensile strength	[9,78,80,81,86,93]		
Toughness of concrete			
Durability	Water absorption (volumetric)	[77,80,81,86,87,92,93]	
	Water absorption (capillary)		
	UPV	[86,87]	
	RCPT	[80,81,86,92,93]	
	RCMT	[87]	
	Electrical resistance	[9,80,81,92,93]	
	Conductivity		
	Chloride profile		
	Resistance to the freeze–thaw cycle	[77,84,89,90]	
	Resistance to water penetration	[9]	
	Abrasion resistance		
	Resistance to sulfates		
	Carbonation depth	[89]	
	Impermeability	[89]	
	SEM	[9,25,85–87,91,92]	
	Others	Specific density	[77,79,82,86]
Bulk density		[77,79]	
Packing density		[86]	
Electrical conductivity		[25]	
Thermal conductivity		[77]	
Water turbidity		[25]	
Temperature		[25]	
pH		[25,81]	
Other	Shrinkage	[83]	
	Surface tension	[83]	
	Fraction	[83]	
	Total cement hydrates (TGA)	[86,91]	
	The thickness of the mortar layer	[76]	
	Porosity (MIP)	[77,82,83,90,91]	
	Bubble diameter (MIP)	[82]	
	Space factor	[84,90]	
	Bubble density	[84]	
	Accelerating the degree of hydration	[80,84,85,87,91,92]	

The study of Kim *et al.* [85] discusses cement mortar, the study of Lan *et al.* [84] about all cement mixtures, and the study of Kim *et al.* [82] about cement paste.

5 Study gaps

There are different types of gaps in the use of MNBs in concrete, including deficit of experimental works, environmental and economic impacts, production challenges, and inconsistencies in concrete performance. For testing deficit, most of the research was done in the mechanical properties of conventional concrete, and less has been carried out in SCC. Limited studies have been done in the field of durability. In the future work, some tests need more work. Related to environmental impact, number of studies is a few. As knowledge of the authors, the economics of using MNBs in concrete has not been studied much so far. Production challenges and inconsistencies in concrete performance are necessary to work. After that, a written code of practice is needed.

5.1 Environmental assessment

The life cycle assessment (LCA) has been done by two methods, the midpoint by use with CML2000 and the endpoint by use with IMPACT2002+, in the CML2000 method, the category of effects of global warming potential (GWP), human toxicity, acidification potential (AP), and freshwater eutrophication (FE) have been investigated. The IMPACT2002+ method evaluates the results of the Life Cycle Inventory (LCI) in the form of human health, ecosystem quality, climate change, and natural resources. Figure 8 shows the damage results on the midpoint of concrete containing MNBs using the CML2000 method [97].

Table 5: Slump classification for conventional concrete BSs Institution [95]

Slump class	Slump value (mm)	Use of concrete
S4	>160	Trench fill In situ piling
S3	100–150	Strip footings Poker or beam Mass concrete foundations Normal reinforced concrete in slabs, beams Walls and columns Sliding formwork construction Pumped concrete Vacuum processed concrete
S2	50–90	Floors and hand-placed pavements
S1	10–40	Kerb bedding and backing

Figure 8 shows that MNB concrete has caused more environmental damage in all classes of midpoint effects evaluated in Taherian's study than conventional concrete. MNB concrete emitted 424.17 kg CO₂ eq in the global warming group, while conventional concrete emitted 386.44 kg CO₂ eq. In fact, MNB concrete emitted 37.73 kg CO₂ eq more in the global warming effect category. The total emission of conventional concrete and MNBs is considered equal to 100%, in this case, conventional concrete has 47.67% and MNB concrete has 52.33% of pollution emissions. In the floor, the acidification effect of conventional concrete is 0.89 kg SO₂ eq and MNB concrete is 0.84. Therefore, in this class, out of 100% of the total emission, 51.45% belongs to MNB concrete and 48.55% belongs to conventional concrete. Notably, in the midpoint technique, the most significant disparity in pollution impact pertains to freshwater eutrophication (FE), indicating a 4.8% higher impact in concrete containing MNBs compared to conventional concrete. Conversely, the least disparity in pollution impact is observed in the human toxicity effect class, with concrete containing MNBs demonstrating only a 2.42% increase in damage compared to conventional concrete [98]. Figure 9 illustrates the damage outcomes at the endpoint of concrete containing MNBs using the IMPACT 2002+ method.

The utilization of concrete containing MNBs marginally elevates environmental pollution indicators in both midpoint and endpoint methods. The total emission of production per cubic meter of conventional concrete and MNBs is considered equal to 100% emission and the contribution of each concrete is shown in Figures 8 and 9. MNB concrete has released a DALY value of 0.000142 in the group of damage to human health, while conventional concrete has released a DALY of 0.000137 pollution into the environment. Therefore, out of 100% of the total damage to human health, 50.90% of the share of concrete is MNBs and 49.10% of the share is conventional concrete. MNB concrete has caused more damage in all classes, but its amount is very close to conventional concrete and does not have a significant difference with conventional concrete, and adding MNBs to concrete slightly increases the amount of damage to the environment [98].

In the life cycle assessment using the endpoint method, the results indicate that the maximum disparity in damage indicators is associated with the climate change category, with a difference of 4.68%. Conversely, the least disparity in the assessment of damage to natural resources is observed in the production phase, where concrete containing MNBs emits only 1.02% more emissions compared to conventional concrete [98]. According to the existing studies of LCA about concrete containing MNBs, the environmental effect of MNBs in concrete is negligible. However, more studies are necessary to determine the impact of MNBs in concrete in the environment precisely.

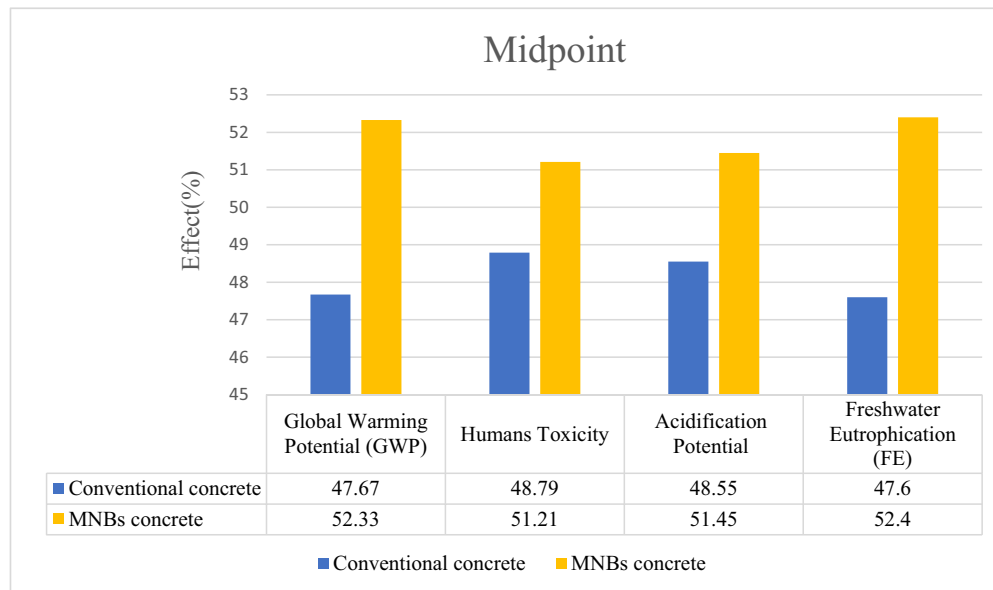


Figure 8: Results on the midpoint of concrete containing MNB using CML2000 method [98].

5.2 Economic assessment

Concrete producers and consumers are mainly looking for optimal quality in mechanical strength and durability to save their costs. Considering this issue, the purpose of this analysis is to find out the economics of concrete production and compare it with the environmental burden. Also, performing economic analysis in this review is important because of the strong role of this topic in the construction industry. Of course, due to the different climatic conditions in the world and the different levels of access, we cannot expect to reach an economic balance in the world.

Taherian [98] compared five types of concretes including MNB concrete, conventional concrete, nano-silica concrete, micro-silica concrete, and geopolymer concrete economically in international. Figures 10 and 11 show the results of economic evaluation and emissions related to global warming and acidification in Taherian's study [98].

The calculation of production cost is based on the rates of the original year. As shown in Figure 10, in the beginning year, the production cost of 1 cm³ of geopolymer concrete had the highest price with a production cost of 1429.322 dollars, but at the same time, by emitting 286.85 kg CO₂ eq, it has emitted less pollution than other concretes and

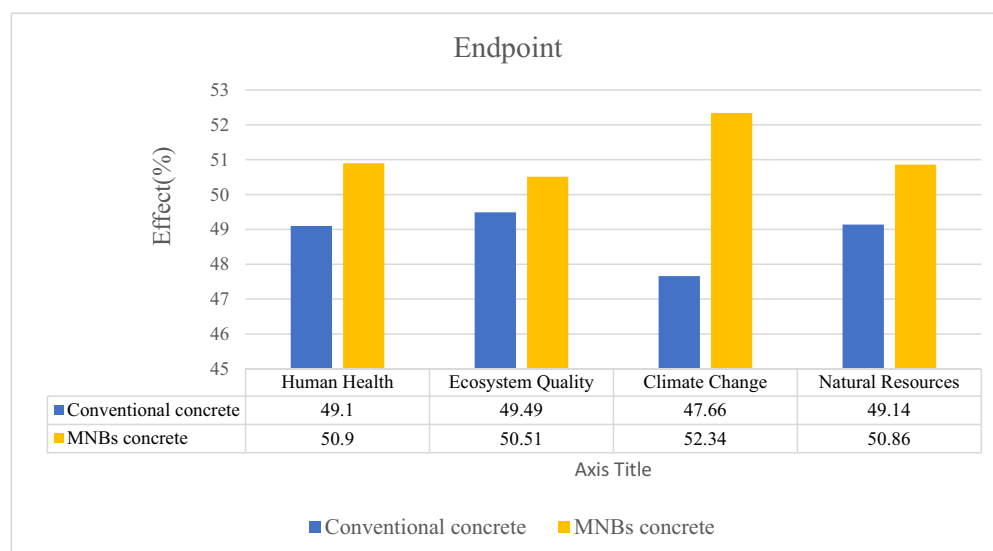


Figure 9: Damage results on endpoint of concrete containing MNB using CML2000 method [98].

has performed best in this respect. After geopolymer concrete, nanosilica concrete cost \$625,047 per cubic meter more than other evaluated concretes. MNB concrete with a cost of \$395.48 has the lowest production cost and also has the best performance in this field by releasing 495.7 kg CO₂ eq after conventional concrete and geopolymer concrete. Micro silica concrete has created the most pollution in the environment by releasing 605.32 kg CO₂ eq and then nano silica concrete has released more pollution than other concretes [98].

Figure 11 shows that the production of microsilica concrete per cubic meter has the most damage in the class of acidification effect on the environment. By introducing 1.55 kg SO₂ eq, this concrete has created more pollution than other evaluated concretes in Taherian's study. Meanwhile, microsilica concrete has a higher production cost than MNB concrete. The production cost of each cubic meter of microsilica concrete was 495.7 dollars [98].

Conventional concrete has caused the least damage to the environment in this index. By releasing 0.84 kg SO₂ eq, this concrete has brought the least pollution to the environment, while its production cost is higher than MNBs and microsilica concrete. As shown in Figure 11, conventional, MNBs, nano silica, and geopolymer concrete have caused less damage in the acidification effect layer, while the

production of each cubic meter of MNB concrete had the lowest production cost and geopolymer concrete had the highest production cost. A total of 625,047 dollars are needed to produce each cubic meter of nano-silica concrete, and in this regard, it was the second most expensive concrete among the concrete evaluated in Taherian's study [98].

Taherian stated that the price of materials (fine and coarse aggregate, cement, MNBs, and other chemical components) for concrete containing MNBs in Iran is about 1% and in the world about 28% less than conventional concrete. However, in this work, the cost of producing MNBW is not taken into account, which will increase the price of concrete containing MNBs. It seems that more economic studies are necessary to reach the real price of MNB concrete [98].

5.3 Advantages and disadvantages of MNBs in concrete

MNBs can be useful as a method to improve the properties of concrete. In concrete with MNB, the thermal stability of concrete increases, and heat transfers from the walls to the

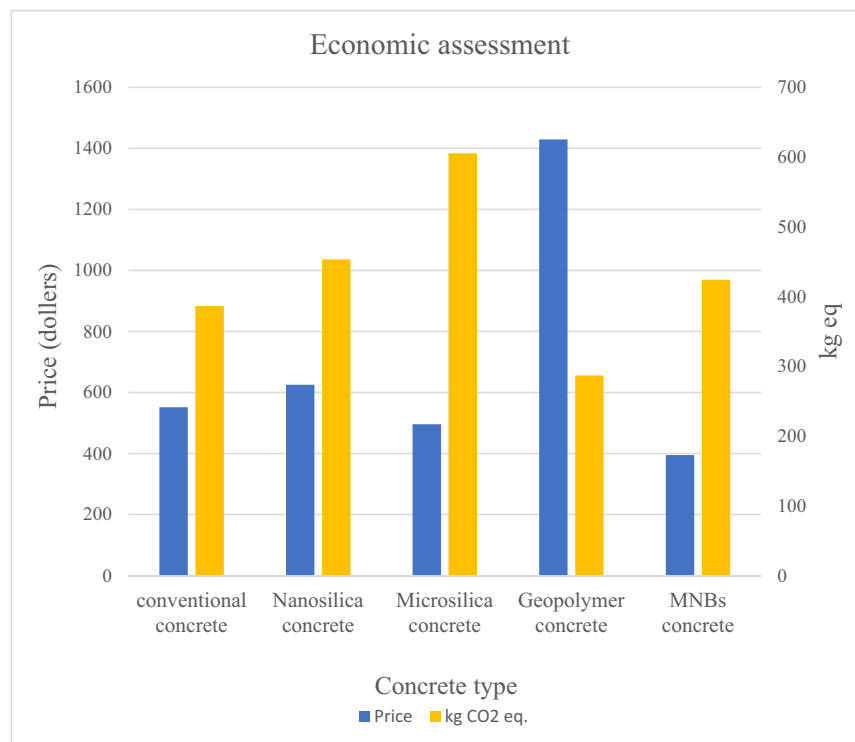


Figure 10: Economic evaluation results and Kg CO₂ eq emissions for concrete types [98].

surrounding environment. MNBs also have sound insulation properties and absorb sound and thus reduce sound penetration in the structure. In addition, MNBs increase mechanical properties such as compressive and tensile strength and show wear resistance. In general, MNBs reduce the workability of concrete slightly and improve durability and MNB concretes reduce the setting time of concrete and help develop the strength of the cement base material and improve the elastic modulus at an early age [9,25,77,86,90]. MNBs have disadvantages such as increasing the cost of making and injecting concrete and conducting more and more detailed tests to ensure the properties of concrete and the newness of its manufacturing technology. It may decrease with changes in environmental conditions (such as temperature and humidity) and reduce the workability properties of fresh concrete [7,99]. The enhancement in mechanical properties and durability of concrete is attributed to the weak alkalinity of nanobubble water and the fact that nanobubbles contract and collapse generating hydroxyl radicals, promoting the hydration reaction of cement to develop hydration products. This densifies the concrete structure and reduces internal pores. Hydrogen nanobubbles, as a nanomaterial, demonstrate desirable effects for meeting high-performance concrete requirements [92].

5.4 Limitations in the industrialization of concrete containing MNBs

One of the challenges of the industrialization of concrete containing MNBs can be the cost of producing this concrete. In addition, the production process of concrete containing MNBs requires complex and precise processes that have not yet been optimized due to the novelty of this technology. Another challenge of this concrete is its durability in the long term, and the useful life of concrete containing MNBs requires more studies to be able to accurately predict its stability and useful life. The supply of raw materials for the production of concrete containing MNBs may not be easily available in some regions of the world.

In various studies, some ambiguities have been mentioned about the basic characteristics of MNBs, including the stability of bulky MNBs, which needs more research [100]. Moreover, despite all those advances, the production of MNB with precise size and concentration control remains a major challenge, particularly for NB. Addressing this challenge may necessitate collaborative interdisciplinary research efforts [14]. Differences in outcomes may occur due to factors such as bubble fabrication methods, their lifespan, and stability. The review emphasizes the need for future iterative experiments with various mixing

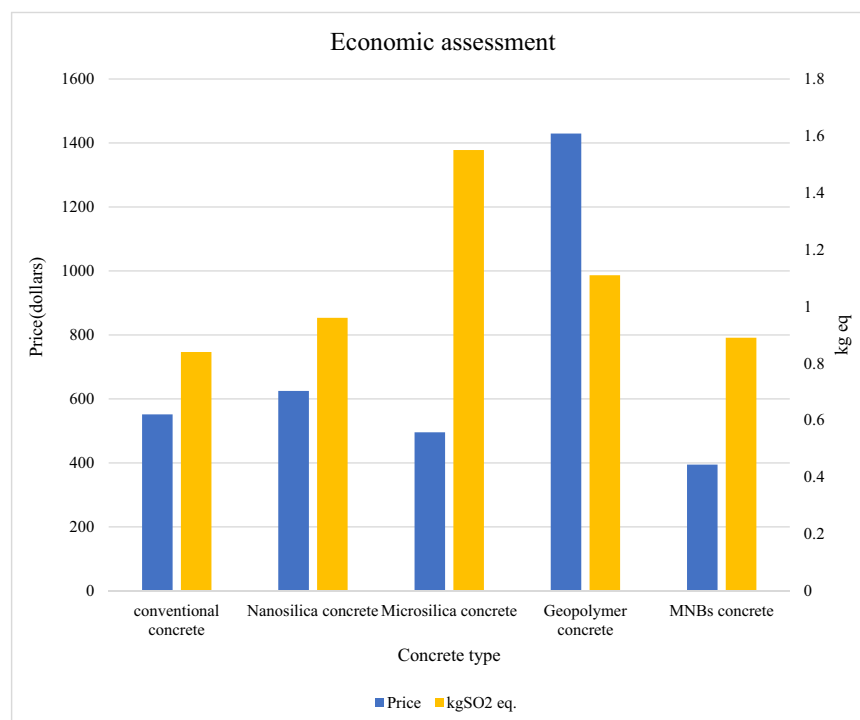


Figure 11: Economic evaluation results and Kg SO₂ eq emissions for concrete types [98].

ratios to reduce random influences and to validate and enhance the reliability of the results [92]. The existence of stable and long-lasting NBs has been confirmed by various experimental studies. However, traditional theoretical models, such as those based on Epstein and Plesset's theory, suggest that nanobubbles should have short lifetimes due to their small size and rapid dissolution from high Laplace pressure [101]. These models, initially designed for larger microbubbles (MaBs), may not be applicable to nanobubbles, which exhibit unique properties like electrostatic repulsion and stable motion influenced by Brownian motion. This conflict between theory and observation highlights the need for new models that account for the specific characteristics of nanobubbles to better explain their existence and stability. Inconsistencies among reports on NBs' fundamental aspects and characteristics create challenges in understanding them. Different studies show varying findings on NBs' size, stability, and behavior, which may result from differences in experimental conditions and methods. These discrepancies hinder a clear and consistent understanding of NBs and highlight the need for standardized experimental methods and reliable models to accurately predict and explain nanobubble behavior.

5.5 Future works

The following areas of research are crucial for future work:

- 1) Due to discrepancies between theoretical models and observations of MNBs, there is a need to develop models that define specific properties of MNBs more accurately.
- 2) Economic analyses of using MNBs in various types of concrete are necessary to assess cost-effectiveness and practical applications.
- 3) Since two-stage concrete (TSC) is environmentally friendly, energy-efficient, and offers benefits such as low drying shrinkage, high bonding resistance, a high modulus of elasticity, and exceptional durability [102–104], it is recommended to study the integration of TSC in MNB concrete.
- 4) Conducting a LCA using MNBs in different types of concretes is essential for evaluating their environmental impact and potential pollution.
- 5) Understanding the long-term effects of MNBs on the mechanical and durability aspects of concrete is vital for sustainable development.
- 6) Testing various mechanical and durability properties is required, including fracture toughness, elastic modulus, temperature effects, depth of water penetration, chloride concentration (28-day measurement from two opposite sides in percentage), the RCMT, mass loss under elevated temperature, and temperature impact.
- 7) In addition, examining the influence of different types of fibers on the workability, mechanical, and durability properties of MNB concrete is recommended.

6 Conclusion

In this review, the characteristics of MNBs and their effect on the properties of fresh and hardened conventional concrete and SCC were assessed. Also, a gap in research using MNBs in concrete is explained. The summary of key points is as follows:

- MNBs reduce the workability and rheological properties of concrete, but the workability is in line with the EFNARC, and the BSs for conventional concrete. In addition, using SAC instead of Portland cement and MNBs in concrete improves rheological properties.
- MNBs cause an early start (almost a teapot) of hydration, which may be useful for shotcrete.
- The presence of MNBs in concrete improves durability (resistance to chloride penetration, UPV, electrical resistance, water absorption, depth of carbonation, and increasing the resistance to the freezing–thawing cycle) and mechanical properties of concrete, including compressive, tensile, and flexural strength of concrete.
- The use of concrete containing MNBs causes a slight increase in environmental pollution indicators. However, more future work is necessary to understand deeply the impact of MNBs on the environment.
- Economic studies show that concrete containing MNBs is cheaper than conventional concrete without taking into account the cost of producing MNBW, although in general, and taking into account all the details of the cost of producing MNB concrete, more economic studies of MNB concrete are also vital.
- Due to existing challenges, such as environmental impact, cost, stability, production challenges, inconsistencies in concrete performance, useful life, and the newness of the production technology of this type of concrete and limited studies in this regard, the industrialization of this concrete is currently limited.
- In this review, it was found that SCC and tests related to fresh concrete have been less interesting and the studies conducted in the field of concrete durability are also very limited.

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