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The mechanical properties of concrete in water environment: A review

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The service performance of concrete structures in a water environment differs from that in a normal environment. An accurate evaluation of the mechanical properties and service status of wet concrete is related to the reliable design and safe operation of concrete structures, e.g., hydraulics, marine engineering, bridges, and tunnels. To promote the application of new and high-performance concrete to complex water environments and grasp the future development trend, the research progress on the service performance of concrete in water environments was reviewed worldwide. Starting from the internal water content of concrete, the existing research is combed, the influence of water content, water pressure, and loading rate on the static and dynamic characteristics of concrete in a water environment is summarized, and the influence mechanism is analyzed. The literature review demonstrates that the static compressive strength of wet concrete is lower than that of dry concrete; however, the elastic modulus improves. With an increase in the strain rate, the compressive strength of wet and dry concretes improves, and the rate sensitivity of the wet concrete is greater than that of the normal concrete. Pore structure characteristics mainly affect the static strength of the wet concrete. The improvement in the dynamic strength of the wet concrete is caused by the combined effect of the concrete rate sensitivity, "Stefan" effect, and water pressure.

KEYWORDS

wet concrete, pore water, static characteristics, dynamic characteristics, review

1 Introduction

Concrete, one of the most widely used building materials, is a typical porous medium and is regarded as a multiphase composite material (Ulrik and MONTEIRO, 1993; Du and LI, 2012). Its internal pore structure exhibits the characteristics of large morphological differences, disorderly distribution, and a large aperture size covering range, which significantly affects its strength, deformation, and durability (Jin et al., 2005).

The process of concrete structure from pouring to service often occurs in different water environments, e.g., moisture in concrete mixing, wet air from water vapor recirculation (Li et al., 2022), and macro water environments in rivers and lakes.

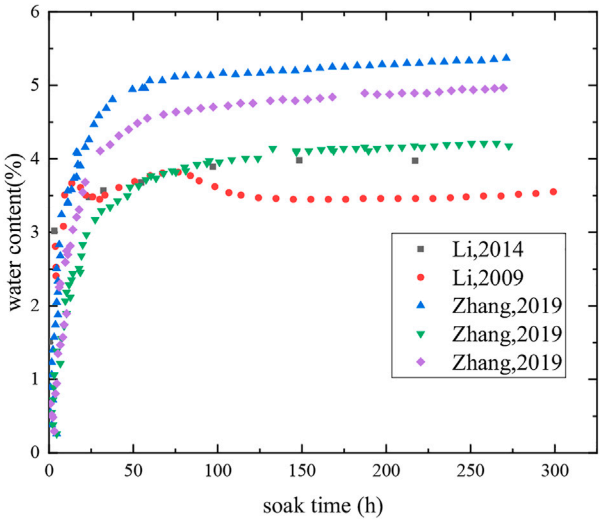

FIGURE 1
Variation in the water content with soaking time.

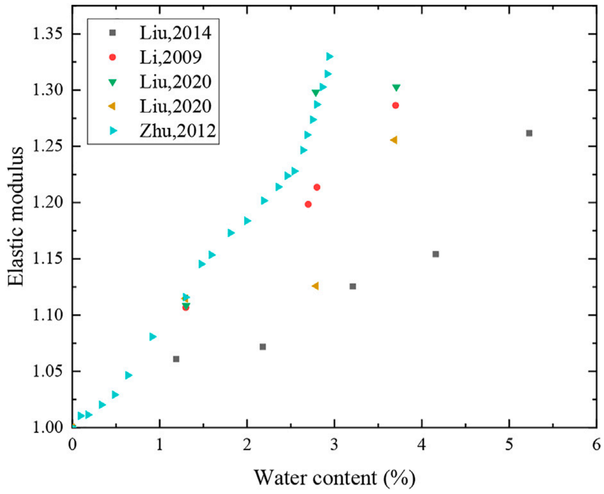

FIGURE 2
Variation in elastic modulus with the water content.

When the concrete has long been in a water environment, water penetrates the concrete through the pore structure, which causes the concrete to be under different humidity states. Studies have demonstrated that (Alexandridis and Gardner, 1981; De Schutter and Taerwe, 1996; Wu et al., 2012; Josué César Bastos et al., 2022) the humidity state affects the mechanical properties of concrete. Simultaneously, the mechanical performance of concrete under static and dynamic loads is significantly different (Bischoff and Perry, 1991; Fu et al., 1991; Javier and MALVAR, 1998), and the water environment makes this difference more complex (Li and WANG, 2006). An extensive study has been conducted on these problems.

Starting from the influence of water environment on the mechanical properties of concrete, this study investigated the mechanical properties change of concrete after water treatment, the law of internal water content change, and the mechanism of pore water on the mechanical properties of concrete and other related studies, and analyzed the potential relationship between water environment and concrete internal water content, water content and concrete mechanical properties. Thus, this paper is narrated from the following aspects: 1) the change rule of the internal water content of concrete in a water environment and its influence on mechanical properties; 2) the effect of pore water on the static and dynamic characteristics of concrete; 3) the influence mechanism of the concrete pore structure, internal water quantity characteristics, and pore water on concrete performance. Furthermore, this study proposes the prospect of a possible development direction in this field.

2 Internal water content and its effects on mechanical properties of concrete

2.1 Water content of concrete in water environment

The internal water content of concrete reflects its humidity state; therefore, the internal water content of concrete and its variation law have been considered as bases for studying the mechanical effect of pore water. Several studies (Li, 2009; Li, 2014; Wang, 2017; Zhang, 2017; Zhang et al., 2019) investigated the change rule of the concrete water content with soaking time in an unconfined water environment. A summary of this is shown in Figure 1. At the beginning of immersion (within 5 h), the water content increased linearly and rapidly and then increased nonlinearly to near saturation. Finally, after a long period of slight growth, it remained constant, which can be regarded as "reaching saturation." Wang et al. (Wang et al., 2017) studied the variation in the water content of underwater concrete under pressure. The water pressure at all the levels (1, 2, 5, and 10 MPa) still conforms to the aforementioned law, and the greater the water pressure, the greater the saturated water content and the shorter the saturation time are. However, in the saturated state, when the water pressure increased from 2 MPa to 5 MPa, the water content increased by 0.77%. When the water pressure increased from 5 MPa to 10 MPa, the water content increased by nearly 0.1%. Finally, when the water pressure was unloaded, the water content decreased gradually (Wang et al., 2017). This indicates that even in the saturated concrete, the pores contain gas, which hinders the infiltration of the pressurized water. When the water pressure was unloaded,

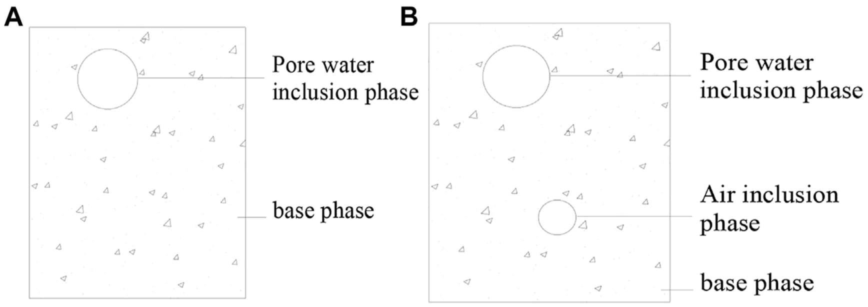

FIGURE 3
Equivalent representative body of concrete **(A)** single-phase inclusion; **(B)** dual-phase inclusion.

the gas pressure discharged the water and returned it to its natural saturated state.

2.2 Influence of water content on the elastic modulus of concrete

Water can be regarded as incompressible relative to air. The pore water in concrete exhibits a greater elastic modulus than air; therefore, the elastic modulus increases with an increase in the water content under the same porosity condition (Nevillea, 1973; Rossi et al., 1992; Mehta and Monteiro, 2014; Zheng and Li, 2011). Liu et al. (Zhu et al., 2012; Liu et al., 2014; Liu et al., 2020) conducted experiments on the influence of the water content on the elastic modulus of concrete. The experimental results (normalization, as shown in Figure 2) support the following conclusion: the elastic modulus approximately and linearly increases with an increase in the water content.

Considering concrete as a multiphase composite material, several researchers (Kuster and Toksöz, 1974; Qiu and Weng, 1990; Yaman, 2002; Yaman et al., 2002; Wang and LI, 2005; Zheng and Li, 2011) have applied the equivalent inclusion theory of mesomechanics (equivalent representative body, as shown in Figure 3), considering the different factors discussed in the calculation formula of the concrete elastic modulus.

$$\frac{K-K_m}{3K+4G_m}=\sum_i^n c_i\frac{K_i-K_m}{3K_i+4G_m} \tag{1}$$

$$\frac{G-G_m}{6G(K_m+2G_m)+G_m(9K_m+8G_m)}=\sum_i^n\frac{c_i(G_i-G_m)}{6G_i(K_m+2G_m)+G_m(9K_m+8G_m)} \tag{2}$$

According to elasticity mechanics, the elastic modulus of concrete is defined as

$$E=\frac{9GK}{3K+G} \tag{3}$$

where K and G are the volume modulus and shear modulus of the concrete matrix, respectively, G_m is the bulk modulus and shear modulus of the matrix without pores, c is the volume fraction of inclusions, and benchmarks i and m represent the inclusion and matrix phases, respectively.

Yama et al. (Yaman, 2002; Yaman et al., 2002) classified pores into active and inactive based on the connection of concrete pores with the outside world and assumed that pore water cannot penetrate inactive pores and environmental humidity affects the elastic modulus of concrete by affecting active pores. By comparing existing calculation models, it was observed that the "Kuster–Toksoz" model (Kuster and Toksöz, 1974) could effectively predict the elastic modulus of wet concrete. However, the model did not consider the influence of pore water on the shear modulus of concrete and the further hydration of cement, resulting in a large deviation between the calculated results and experimental data. Zheng et al. (Zheng and Li, 2011) and Wang et al. (Wang and LI, 2005) considered the deformation of pores, microcracks, pore water viscosity, and further hydration of cement. The modified model exhibits good applicability to the experimental data (Yaman et al., 2002). However, the aforementioned studies considered concrete as the inclusion of the matrix phase and saturated pore water phase, which is not suitable for wet concrete.

Based on the Mori–Tanaka theory (Qiu and Weng, 1990), Wang et al. (Wang and Li, 2007) considered the effects of water viscosity, late hydration of cement, and pore geometry on the elastic modulus of wet concrete. They used the modified differential decomposition method of mesomechanics to decompose unsaturated concrete into saturated concrete equivalent medium and dry pores and assumed that the elastic properties of the unsaturated concrete depended on the water content, pore geometry, and elasticity of the matrix concrete. Bai et al. (Bai et al., 2010) regarded concrete as the inclusion of the matrix, air, and pore water phases, and these two modified models can effectively predict the elastic modulus of wet concrete. A comparison of the theoretical models above, as

TABLE 1 Comparison between the elastic modulus prediction models of wet concrete.

References	Theoretical foundation	Inclusions	Considerations	Scope of application
Yama et al., 2002 (Yaman et al., 2002)	"K-T" model	Single-phase inclusion	—	Saturated, dry concrete
Zheng et al., 2011 (Zheng and Li, 2011)		Single-phase inclusion	Pore deformation, viscosity of water, and further hydration	Saturated, dry concrete
Wang et al., 2005 (Wang and LI, 2005)	"M-T" model	Single-phase inclusion	Viscosity of water and further hydration	Saturated, dry concrete
Bai et al., 2010 (Bai et al., 2010)		Dual-phase inclusion	Viscosity of water and further hydration	Wet concrete
Wang et al., 2007 (Wang and Li, 2007)		Dual-phase inclusion	Microcracks, viscosity of water, and further hydration	Wet concrete

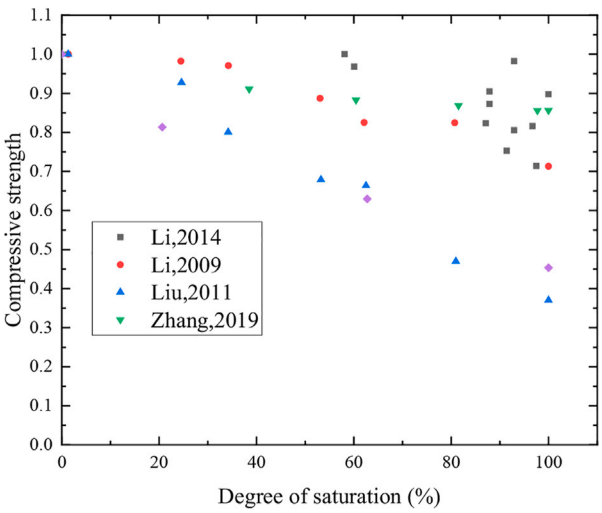

FIGURE 4
Compressive strength of concrete with different saturation.

shown in Table 1, indicates that a model with more inclusions has a greater scope of application.

2.3 Influence of the water content on the compressive strength of concrete

Researchers (Cadoni et al., 2001; Yan et al., 2005; Wang and LI, 2006a; Wang and LI, 2007a) conducted the strength test of concrete with different water contents, and the results indicated that wet concrete exhibited higher compressive strength than dry concrete. Wang et al. (Wang and LI, 2006a; Wang and LI, 2007a; Wang and LI, 2007b) compared the strength of saturated and dry concrete, and the results indicated that the compressive strength of the saturated concrete decreased by 4.5%, and the splitting tensile strength decreased by 11.41% compared with that of the dry concrete. Li et al. (Li, 2004) studied the influence of different water–cement ratios and soaking times on the strength of dry concrete and obtained similar results. With an increase in soaking time, the compressive strength of the concrete decreased, and the influence of humidity on the concrete with a high water–cement ratio was evident. A few researchers (Reinhardt et al., 1990; Ross and DAVID, 1996; DavidHARRIS CEM, 2000) conducted tests on the saturation of concrete specimens, and the results indicated that the strength of concrete decreased with an increase in saturation.

Li et al. and Zhang et al. (Li, 2009; Liu et al., 2011; Li, 2014; Zhang et al., 2019) studied the change rule of the water content of dry concrete after immersion and its influence on the compressive strength. The normalized results are illustrated in Figure 4. Although the data were discrete, the compressive strength decreased with an increase in saturation. These studies regarded water content as the main influencing factor, ignoring the influence of internal porosity on strength. Existing studies (Lian and Zhuge, 2010; Lian et al., 2011; Yu et al., 2015; Zhou et al., 2015) demonstrate that porosity adversely affects the compressive strength and elastic modulus of concrete. Therefore, under the same mix proportion and material conditions, the higher the saturation of concrete, the stronger the water absorption capacity of the concrete is, and the greater the internal porosity, the lower the strength is.

Moreover, the water content affects the fracture performance of concrete. Deng et al. (Deng et al., 2014) studied variations in the fracture properties of concrete immersed in water. It was observed that the fracture toughness decreased with an increase in the immersion time, and the decrease trend was first increased and then decreased. Wittmann et al. and Zhang et al. (Wittmann et al., 2007; Zhang et al., 2010) observed that completely dry concrete exhibited higher fracture energy, and the fracture energy of the concrete in the dry state was 1.18 and 1.57 times the saturation of 75% and 100%, respectively. Similar results were obtained by Ross et al. (Rossi and Boulay, 1990; Rossi, 1994; Zhang et al., 2016).

3 Effect of pore water on the mechanical properties of concrete

When the concrete structure is at a certain depth in the water environment, it is subjected to water pressure that cannot be ignored. Simultaneously, different pore water pressures were generated at different surface depths of the structure. The pore water pressure inside the concrete surface is the same as the environmental water pressure (Bažant and Najjar, 1972). Compared with the study of concrete performance in a non-pressurized water environment, the pressurized water environment is closer to engineering practice.

3.1 Effect of pore water on the static strength of concrete

Researchers have conducted studies on the static strength of concrete under different water pressures, and no conclusions have been reached. Haynes et al. (Haynes and Highberg, 1976) performed out a static uniaxial compression test of concrete at a water depth of 6,100 m, and its strength decreased by 10% compared with the reference group. Subsequently, Bjerkli et al. (Bjerkli et al., 1993) studied the mechanical properties of concrete under water pressures at 400 and 800 m and observed that under the same curing and testing conditions, water pressure did not indigenously affect the compressive strength of the concrete.

Li et al. and Du et al. (Du et al., 2009; Li and DU, 2011) placed concrete of different maximum aggregate sizes under pressurized water to study the effects of water pressure and action time on the compressive strength of the concrete. The results indicated that when the maximum aggregate size was the same, the compressive strength loss rate increased with an increase in the water pressure and action time. When other conditions are the same, the larger the maximum aggregate particle size, the greater the compressive strength loss rate is. Xue et al. (Xue et al., 2020) observed that under high pore water pressure, the uniaxial compressive strength of concrete decreased with an increase in the exposure time and water pressure. At this instant, the uniaxial load exhibits four stages: elastic, stable crack propagation, unstable crack propagation, and failure. Tian et al. (Tian et al., 2014; Wang, 2017) studied the mechanical properties of saturated concrete at water pressures of 0, 2, 5, and 10 MPa. The results indicated that the compressive strength increased with an increase in water pressure when the strain rate was 0.01/s, and the maximum increase was 83%. Zhang et al. and Zhou et al. (Zhang, 2017; Zhou et al., 2020) conducted similar experiments and obtained similar results.

Furthermore, researchers have studied the multiaxial loading under water pressure. Tian et al. and Peng et al. (Tian et al., 2014; Peng et al., 2015) conducted constant triaxial tests on concrete under different pore water pressures. It was observed that the strength of concrete under natural drying conditions was greater than that of saturated concrete, and the peak stress and strain of concrete increased with an increase in confining pressure (Imran and PANTAZOPOULOU, 1996). Li et al. (Li et al., 2007) and Chen et al. (Chen et al., 2010) studied the compressive strengths of dry and saturated concrete under water pressure and triaxial stress. The test results indicated that the strength of dry and saturated concrete increased with an increase in the confining pressure under sealing conditions, and the confining pressure effect of dry concrete was evident. When the specimen was directly exposed to water, the compressive strengths of the dry and saturated concretes significantly decreased. Under confining pressures of 2 and 4 MPa, the compressive strength of the dry concrete decreased by 56.8% and 62.1%, and that of saturated concrete decreased by 15.3% and 30.9%, respectively. Vu et al. (Vu et al., 2009) conducted triaxial compression tests under confining pressures of 20–650 MPa, and the results indicated that the shear strength of the dry concrete almost linearly increased with confining pressure increase. Under a confining pressure of 200 MPa and above, the ultimate compressive strength of concrete decreases with an increase in saturation.

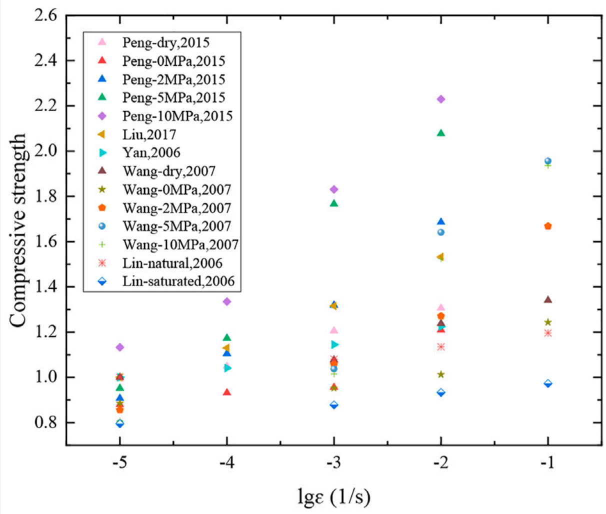

FIGURE 5
Compressive strength of concrete under different loading rates.

3.2 Effect of pore water on the dynamic strength of concrete

Owing to the viscosity and incompressibility of pore water, the occurrence and expansion of internal cracks and the formation of macroscopic cracks in concrete under dynamic loads differ from those in the natural state (Fu et al., 2021). In addition, the rate sensitivity of concrete makes its dynamic strength in a water environment different from that in the natural state (Cao et al., 2010).

Researchers (Klepaczko and BRARA, 2001; Mori, 2001; Lin and YAN, 2006; Yan and LIN, 2006; Liu et al., 2017) have studied the compressive strength of concrete under different water pressures and loading rates. The normalized results are shown in Figure 5. The results indicated that the compressive strength of dry concrete and wet concrete increased with an increase in the strain rate. When the strain rate is 10^{-5}/s, the dry concrete has a higher compressive strength; however, with an increase in the strain rate, the difference between the compressive strengths of wet concrete and dry concrete is narrowed and even slightly reversed. Wang et al. (Peng et al., 2015; Wang et al., 2017) demonstrated that the compressive strength of concrete increased with an increase in water pressure at the same strain rate. When the water pressure was 10 MPa, the compressive strength increased by 84.4% compared with that at 0 MPa. The water pressure increased the sensitivity of the concrete to the strain rate, and the increase was 144.9% when the water pressure was 5 MPa. In addition, it is observed that the water content and strain rate affect the failure mode of concrete; when the water content of the wet concrete is 1.27 times higher than that of the natural state, the cone failure of the concrete will occur under rapid loading, and with an increase in the water content and strain rate, the area of the crack surface and the amount of debris shedding of the specimen decrease as well; when the water content of concrete is lower than that of the natural state or under slow loading, oblique shear failure occurs (Wang et al., 2016a).

Lin et al. (Lin and YAN, 2006) studied the effect of water content on the strain-rate effect of concrete. The ultimate compressive strength of the saturated concrete at a quasi-static strain rate was lower than that of the natural concrete; however, the saturated concrete exhibited a higher strain rate sensitivity. Zhang et al. and Li et al. (Li, 2014; Zhang, 2017) performed dynamic compression tests in a water environment (Loading speed 0.05–3 MPa). It was observed that humidity increased the rate effect of the concrete compressive strength, and the compressive strength increased exponentially with the loading rate under the same humidity. In general, the rate effect of wet concrete is more evident than that of natural concrete, and an increase in water pressure aggravates the rate effect of the concrete.

Under biaxial compression, Wang et al. (Wang et al., 2016b) observed that the static compressive strength of dry concrete was greater than that of saturated concrete; however, this observation is in contrast to the results under high strain rates. The influence of the strain rate on the saturated concrete is evident, especially when subjected to lateral constraints. A few researchers have indicated that the mechanical properties of wet concrete decrease within a specific strain-rate range. Ding et al. (Ding and ZHOU, 2014) observed that under a dynamic load of 50/s, the dynamic compressive strength of concrete decreased with an increase in the water content, and the maximum decrease was 25.35%. Zhou et al. (Zhou et al., 2011) observed that when the strain rate was 10^{-2}/s, the compressive strength of concrete decreased with an increase in the water content.

4 Influence mechanism of water environment on mechanical properties of concrete

When the concrete is in a water environment for a long time, water infiltrates into the concrete along the opening pores of the concrete, so that the concrete is under different humidity conditions, thereby exhibiting different water contents. As mentioned above, in the study of the effect of concrete water content or saturation on its compressive strength, the water content or saturation as the only index does not completely exclude the interference of the structural characteristics of concrete pores. According to the study results, the specimen with water content exhibited a smaller compressive strength; however, the higher the water content, the more space the specimen held water, i.e., there was a larger porosity, and the strength was bound to be smaller. Therefore, it is necessary to determine the relationship between the pore characteristics and strength. In addition, the interference of porosity should be excluded as far as possible in future studies.

As a dense material, the internal humidity response of concrete is not uniform when it is in a water environment. Therefore, a humidity gradient is present inside. Relevant studies have demonstrated that the humidity gradient influences the mechanical properties of wet concrete. When wet concrete is subjected to static load, the pore water, like a wedge, may accelerate crack propagation. When the wet concrete is subjected to rapid loading, pore water has a certain inhibitory effect on the occurrence and propagation of cracks, and the pore water pressure and “Stefan” effect affect the dynamic strength of concrete.

4.1 Influence mechanism of pore distribution on mechanical strength of concrete

Pore structures exist in aggregates, cementitious materials, and interface transition zones and can be divided into primary and secondary pores. The internal pore structure possesses the characteristics of large morphological differences, disorderly distribution, and wide pore size coverage, which significantly impact the strength, deformation, and durability of concrete (Luna-Galiano et al., 2016; Zhang et al., 2020; Liu et al., 2021; Chen et al., 2022; Ren et al., 2022). However, not all pore structures adversely affect concrete performance. For instance, the pore structure can serve as a water supply channel for the

TABLE 2 Comparison of early models with regard to the relationship between compressive strength and porosity of concrete.

References	Model	Remark
Balshin et al., 1949 (Balshin)	$\sigma = \sigma_0 (1 - P)^b$	b, k, n, and c are the empirical constants
Ryshkewitch et al., 1953 (Eugene, 1953)	$\sigma = \sigma_0 e^{-kP}$	
Schiller et al., 1971 (Schiller, 1971)	$\sigma = n \ln (\sigma_0 / P)$	
Hasselman et al., 1969 (Hasselman, 1969)	$\sigma = \sigma_0 - cP$	
Chen et al., 2012 (Chen et al., 2013)	$\sigma = \sigma_0 [(\frac{P_c - P}{P_c}).(1 - P^{2/3})]^{1/2}$	P_C is the porosity under the failure threshold
Lian et al., 2011 (Lian et al., 2011)	$\sigma = B\sqrt{(1-p)^m e^{-np}}$	B, m, and n are the empirical constants

TABLE 3 Comparison of the relationship models with regard to compressive strength and the porosity of concrete.

References	Model	Remark
Rakesh and BHATTACHARJEE (2003)	$\sigma = K_2 C (1 - P)/\sqrt{d_m}$	K_2 is the experimental constant, C is the cement content of mix, expressed as fraction
Zhao et al. (2014)	$\sigma = K\, exp[\frac{B\alpha(1-P)}{\sqrt{d_m}}]$	α is the degree of hydration, and d_m is the average pore size
Bu and TIAN (2016)	$\sigma = \sigma_0 \exp(aP + bL + cr_2' + dd_0)$	L is the total pore volume parameter, r_2' is the pore shape parameter, and d_0 is the critical pore diameter. The aforementioned parameters can be obtained from the MIP curve
Zhang et al. (2021)	$\sigma = \alpha K_2 \sqrt{B_s} C (1 - P)/\sqrt{d_m}$	C is the cement content parameter, K_2 is the experimental constant, B_s is the sensitive pore size distribution coefficient, and α is the coefficient
Li et al. (2018)	$\frac{\sigma}{\sigma_0} = 1 - K[1 - \frac{(1-c)^2}{5c+1}]$	K represents the total influence factor determined by the pore size of concrete, $c = a^2/b^2$, a, b as shown in Figure 6
Jin et al. (2017)	$\sigma = b \cdot (D_s/V_c)^a$	a and b are constants, D_s is the fractal dimension, and V_c is the volume of pores

continuous hydration of cementitious materials and provide space for the growth of hydration products. Wu (Wu, 1979) classified pore structures into harmless pores (<20 nm), less harmful pores (20–50 nm), harmful pores (50–200 nm), and harmful pores of >200 nm based on the pore size. Based on this observation, several scholars have explored the relationship between the pore structure characteristics and strength considering various influencing factors.

Early studies established a relationship model between porosity and strength considering the relationship between porosity and strength (Table 2). In the formula, p is the porosity of concrete, σ_0 is not always reliable for characterizing the strength of the porous material or calculating the strength of the specimen to the strength of porosity of 0, and the pore structure characteristic parameters that affect the strength include pore volume, pore effective diameter, pore surface area, and pore spacing coefficient (Li and ZHAO, 2021). The aforementioned model was not considered; therefore, it is not accurate in practical applications.

Moreover, scholars have tried to build comprehensive and applicable models, considering factors other than porosity (Table 3). Bu et al. (Bu and TIAN, 2016) extracted the pore structure characteristic parameters, e.g., porosity and pore size distribution, based on Mercury Intrusion Porosimetry (MIP) technology and established an exponential model of pore structure characteristics and strength. Zhao et al. (Zhao et al., 2014) established an extended the "Bhattacharjee" model (Rakesh and BHATTACHARJEE, 2003) considering porosity, average pore size, and hydration degree, which can clearly describe the relationship between the pore structure characteristics and strength of cement mortar. Based on this model, Zhang et al. (Zhang et al., 2021) analyzed the influence of pore size distribution on strength, obtained the sensitive pore size that affects the compressive strength of concrete, and corrected the existing model according to the sensitivity coefficient. The results indicated that this model possessed a greater correlation with the calculation results than the existing model. Li et al. (Li et al., 2018) proposed a simplified central-hole model (Figure 6) based on the three-phase and hollow sphere models. Explicit expressions for tensile strength, compressive strength, and porosity were derived considering the influence of the pore size. The results indicated that the compressive strength of concrete decreases with an increase in porosity, and the decrease in compressive strength is greater than that in tensile strength. The strength of concrete can be improved by reducing its pore size. In addition, a few scholars (Jin et al., 2017; Han et al., 2022) have used the fractal theory to characterize the pore size distribution and proposed new pore characteristic parameters. The established functional relationship model demonstrated a good prediction accuracy.

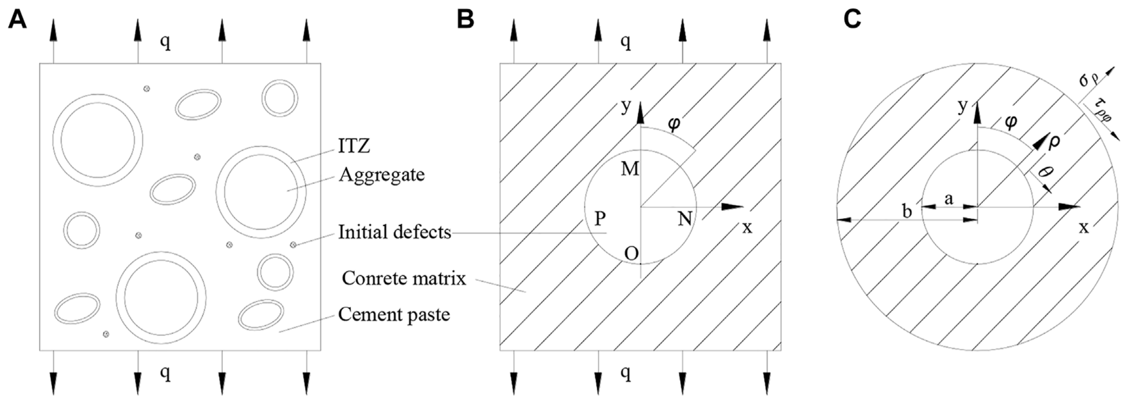

FIGURE 6
Equivalent process **(A)** stress state of a representative element; **(B)** a simplified central pore model; **(C)** equivalent polar coordinate model of (B) (Li et al., 2018)

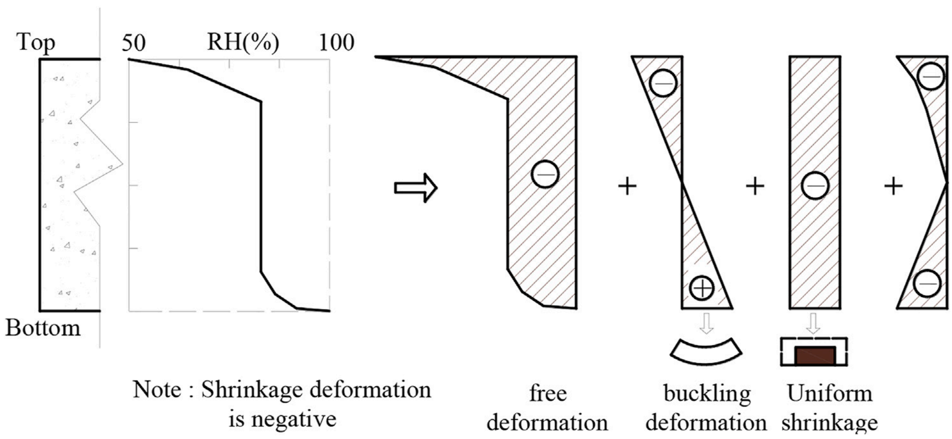

FIGURE 7
Deformations due to a moisture gradient in jointed concrete pavement.

4.2 Mechanism of pore water on concrete strength

4.2.1 Mechanism of humidity gradient on concrete strength

A few researchers believe that the internal humidity gradient of wet concrete will affect its strength. Xu et al. (Xu et al., 2017) studied the internal water content, distribution, and change law of concrete and observed that the internal moisture change of concrete was caused by the hydration reaction, evaporation, and free migration of water. The migration was divided into two stages. The first stage included upward migration caused by the density of water and solids, and the migration rate was the quadratic function of the water content. The second stage was caused by the humidity gradient and follows Fick's law. Larrard et al. (Larrard et al., 1992; Gao et al., 2013; Xu et al., 2017) demonstrated that it was difficult for concrete to reach full saturation, and a humidity gradient existed inside, which will certainly impact the concrete performance. Popovic et al. (Popovics, 1986) stated that the internal moisture migration of concrete produces uneven deformation, which produces tensile and compressive stresses in the concrete and reduces its strength. Wei et al. (Wei, 2012; Gao and WEI, 2014) studied the formation law of humidity gradient inside the concrete pavements, analyzed the influence of humidity gradient on the shrinkage deformation and stress of concrete, and established the calculation method of warping deformation and stress caused by humidity. They conducted that the nonlinear humidity gradient caused the nonlinear shrinkage of concrete slab along the depth direction. This shrinkage deformation can be divided into two

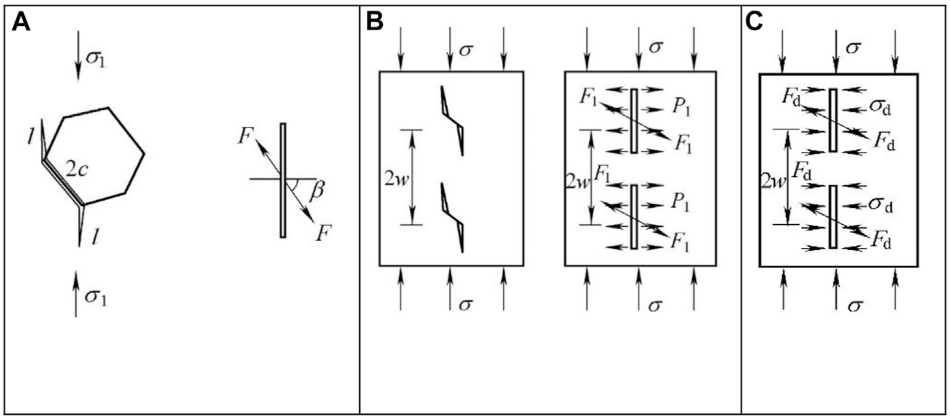

FIGURE 8
Wing cracks under the uniaxial load **(A)** wing crack; **(B)**, **(C)** two interacting cracks and their equivalent forms (Gao and WEI, 2014)

macro deformation modes of uniform shrinkage and warping, and the other part of the deformation is transformed into internal stress by internal constraints (as shown in Figure 7). Li et al. (Li and ZHENG, 2012) regarded that the humidity gradient makes the elastic modulus of each part of wet concrete different, resulting in different stresses, so the failure mode of wet concrete is different from that of dry concrete. The aforementioned studies have explained the reason for the decrease in the strength of wet concrete to a certain extent; however, relevant studies have confirmed that even if there is no humidity gradient, pore water affects the mechanical properties of concrete. Thus, this influence mechanism needs to be further studied.

4.2.2 Mechanism of pore water pressure on concrete strength

Wittmann (Wittmann, 1973) stated that the decrease in the static mechanical properties of wet concrete is caused by the separation of cementitious particles using pore water, which reduces the van der Waals force and surface energy (Wang et al., 2008), thus reducing the critical stress of the cracks. Kaplan et al. (Seyit, 1980; Tetsuri and CHIKAKO, 2014) stated that when concrete was subjected to load, the pores and channels perpendicular to the load direction were closed, and free water flowed inside the concrete. The viscosity of the water caused a pore water pressure gradient. Under a high loading rate, the pore water pressure increased, and the occurrence of cracks in the solid phase was delayed, thereby increasing the compressive strength of the concrete. Rossi et al. (Rossi, 1991a; Rossi, 1991b) used the “Stefan” effect to explain why the cracking process and mechanical properties of wet concrete at high strain rates are different from those of reference concrete. The “Stefan” effect refers to the existence of a thin layer of mucous membrane (water, oil, and other viscous liquids) between two flat parallel plates at a certain distance, and the reverse force will occur when the two plates are separated at a certain speed. The greater the speed, the greater the reverse force is (Zhou, 2007). Rossi regarded microporous and capillary walls as two parallel plates. When concrete is subjected to a dynamic load, the internal microstructure is deformed by extrusion, and the deformation time is short. Therefore, the large reverse force may be the reason for the increase in the rate sensitivity of the wet concrete.

Most of the aforementioned studies are qualitative descriptions and discussions based on test results and lack systematic theoretical studies. Based on the “Stefan” effect, Wang (Wang and LI, 2006b) systematically analyzed the pore water pressure mechanism affecting the static and dynamic compressive strengths of saturated concrete based on elasticity and fracture mechanics. The wing cracks are shown in Figure 8. They are used for calculation, and considering the interaction between the two cracks, the static compressive strength of saturated concrete is defined as

$$\sigma_{cs} = \frac{K_{1c}}{T(\cdot)} \tag{4}$$

$$T(\cdot) = \frac{2c\cos\beta_0\left[\cos\beta_0\sin\beta_0 - \mu\left(\cos^2\beta_0 - a_1\right)\right]}{\sqrt{w\sin\left(\frac{\pi c\sin\beta_0}{w}\right)}} + a_1\sqrt{2w\cot\left(\frac{\pi c\sin\beta_0}{2w}\right)} \tag{5}$$

$$K_1 = \frac{F_1\cos\beta}{\sqrt{w\sin\left(\frac{\pi l}{w}\right)}} + p_1\sqrt{2w\tan\left(\frac{\pi l}{2w}\right)} \tag{6}$$

where K_1 is the strength factor at the crack tip; β_0 is the value when K_1 considers the maximum value, which is a function of the friction coefficient between cracks; a_1 is the relationship coefficient between pore water pressure and external pressure stress; l is the length of the airfoil crack; c is the half of the length of the oblique crack; w is the half of the crack spacing.

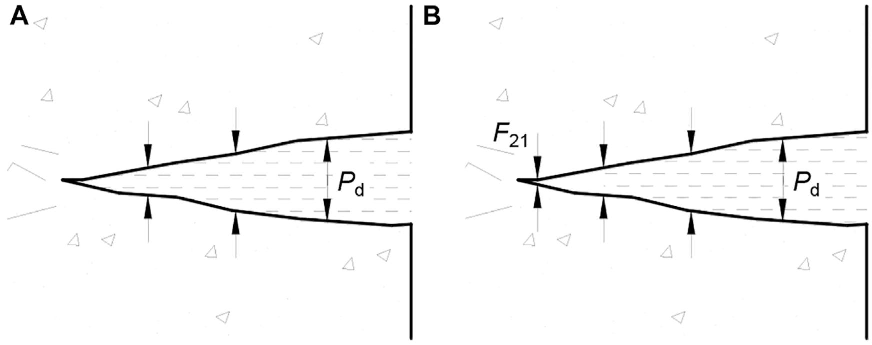

FIGURE 9
Water pressure distribution in cracks under different loading rates **(A)** water reaches the crack tip under slow loading; **(B)** water cannot reach the crack tip under fast loading.

Under rapid loading, the free water in the crack did not easily reach the crack tip (Figure 9), and σ_d is generated by the reaction force under the "Stefan" effect. Under dynamic loading, the stress intensity factor of the crack is defined as

$$K_{Id} = k(v) \cdot K_I \tag{7}$$

Assuming that the actual fracture toughness of concrete matrix does not change with the loading rate, the dynamic compressive strength of concrete is defined as

$$\sigma_{cd} = \frac{K_{Ic}^{d} + k(v) \cdot \sigma_d \sqrt{2wcot\left(\frac{\pi csin\beta_0}{2w}\right)}}{2ck(v)D(\beta_0)} \sqrt{wsin\left(\frac{\pi csin\beta_0}{w}\right)} \tag{8}$$

where $k(v)$ is the influence coefficient of the crack growth rate with regard to the stress intensity factor at the crack tip, $D(\beta_0) = \cos\beta_0$ [$\sin\beta_0\cos\beta_0$-μ ($\cos2\beta_0$-a_2)-B_1], a_2 is the water pressure coefficient, and B_1 is the viscosity coefficient; other symbols have the same definition.

Eqs. 4–8 are only applicable to dry or saturated concrete. Based on this, the factors influencing the pore water pressure of unsaturated concrete have been considered, as expressed in Eq. 9, and the aforementioned calculation formula has been modified in one of the studies (Wang and LI, 2006a) for application to general wet concrete.

$$\begin{cases} p = a_1(\varepsilon_V, S, V)\sigma & \sigma \le \sigma_c \\ p = a_2(\varepsilon_V, S, V)\sigma & a_2 < a_1, \sigma < \sigma_c \end{cases} \tag{9}$$

where p is the pore water pressure; a_1 and a_2 are the coefficients of the relationship between the pore water pressure and the external load when the concrete volume is in the state of compression and expansion, respectively, and they are related to volume deformation ε_v, saturation S and crack propagation velocity V; in addition, a_2 is related to the damage degree D of concrete; σ_c is the stress value when the volume compression of concrete is maximum.

The aforementioned study attempted to reveal the influence mechanism of pore water pressure on the static and dynamic compressive strength of wet concrete based on the theoretical level. When the loading rate was low, the free water in the pore could reach the micro-crack tip and be affected by the deformation of the concrete matrix. The pore water acted as a "wedge" to accelerate crack propagation and reduced the compressive strength of wet concrete. When the loading rate was high, the crack propagated rapidly, and it was difficult for pore water to reach the crack tip. Under the combined action of the pore water pressure and "Stefan" effect, the crack development was hindered, dynamic compressive strength of the wet concrete improved, and wet concrete exhibited more rate sensitivity than the dry concrete.

5 Conclusion

Several achievements have been obtained in research on the mechanical properties of wet concrete. In this study, the influence of water on the mechanical properties of concrete is reviewed. The following points have been concluded:

1) The static compressive strength of wet concrete was lower than that of dry concrete; however, the elastic modulus improved. This is because the water content of the concrete is positively correlated with porosity, and the strength decreases with an increase in porosity. However, the elastic modulus of water is greater than that of air; therefore, the elastic modulus increases with an increase in the water content.
2) With an increase in the strain rate, the compressive strengths of wet and dry concretes increased; however, the rate sensitivity of the wet concrete was more evident than that of the dry concrete. This is because the concrete exhibits a

high rate sensitivity, coupled with the pore water pressure and "Stefan" effect, making the rate sensitivity prominent.

Previous studies on the relationship between the moisture state and mechanical properties of concrete have used drying and soaking methods to obtain specimens with different water contents, and the influence of porosity on concrete performance has not been excluded. In addition, most existing studies provide qualitative explanations based on experimental results, and a few provide quantitative explanations based on the theoretical level. Thus, future studies should focus on the following points:

1) While considering water content as a variable to study the concrete strength, the influence of irrelevant variables, e.g., porosity, can be excluded. Using the same specimen or a specimen with similar porosity, accurate pore characteristics and moisture migration information can be obtained based on X-ray Diffraction (XRD), Computed Tomography (CT), nondestructive testing, and other technologies.
2) Multifactor coupling tests, e.g., impact load, multi-axial stress state, and high-pressure water environment, can be conducted to meet the requirements of cement-based materials in complex water environments.
3) Theoretical studies on changes in the mechanical properties of wet concrete can be conducted based on various assumptions and models to further study and quantify the influence of water on the mechanical properties of fresh and hardened concrete.

Author contributions

JW: Conceptualization, Methodology, Investigation, Data curation, Writing—original draft. KS: Investigation, Formal analysis, Data curation, Writing—review and editing. YH: Resources, Writing—review and editing. QG: Resources, Writing—review and editing, Funding acquisition. QL: Resources, Validation, Writing—review and editing, Supervision, Funding acquisition.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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