

Unlocking the role of water on the early age strength development of zero-slump concrete: Prediction of the optimal water content

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ABSTRACT

Zero-slump concrete (ZSC) with low water and binder contents must develop sufficient early-age strength to withstand outdoor stacking loads. However, rational mix design remains challenging because the role of water content in early-age compressive strength development is not yet clearly understood. This study aims to investigate the role of water content in the early-age compressive strength development of ZSC. Experimental results demonstrate that, at a given packing density (PD), compressive strength of ZSC evolves through three distinct stages with increasing water volume: an increasing stage, a flattening stage, and a decreasing stage, which differs from the behavior of conventional concrete. A solid particle distribution model is proposed to explain the mechanisms governing this development, attributing it to water-induced variations in cement particle spacing and autogenous shrinkage. Based on this model, a prediction method is developed and validated across different ZSC mix designs. Overall, the findings provide a unified mechanistic framework for a practical mix design approach to optimize water content and mitigate its detrimental effects on compressive strength development in ZSC.

1. Introduction

Unlike conventional flowable concrete, zero-slump concrete (ZSC), also referred to as roller-compacted concrete, is characterized by a very stiff consistency (slump < 6 mm) due to its low water content, and therefore requires mechanical compaction for shaping [1, 2]. This characteristic provides two key production advantages. First, owing to its stiff consistency, ZSC develops sufficient green strength after compaction to allow immediate demolding without conventional formwork, followed by direct transfer to curing chambers with relative humidity typically above 80%. Second, the fresh ZSC mixture can be easily transported to the compaction equipment, as it retains a granular-like state after mixing rather than forming a fluid mixture. With these advantages, ZSC is particularly well suited for large-scale precast concrete production. The European precast sector comprises over 5500 companies operating nearly 8000 plants, with annual production reaching approximately 4.6 million tonnes in Spain and nearly 12 million tonnes in Belgium [3,4].

ZSC is commonly subjected to short-term curing in a controlled chamber before being moved and stacked for subsequent air curing [3,5]. Therefore, achieving adequate early-age strength to resist stacking loads is critical for production efficiency. In precast plants, the early-age strength of ZSC is governed by both curing conditions and mix design. When curing conditions are fixed, optimizing the mix design becomes essential for achieving the desired early-age strength. Among mixture parameters, water content plays a critical

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role because it governs both the packing density (PD) after compaction and the overall water-to-binder ratio (w/b), which together control early-age strength development. The influence of water content on compaction and strength development is non-monotonic and depends on the water-content range. Within the appropriate water-content range, a relatively higher water content can act as a lubricant, reducing particle friction, increasing PD, and thereby enhancing strength under the same compaction conditions. However, unlike conventional concrete, ZSC used for pavement blocks typically contains a low cement dosage ($210\text{--}360\text{ kg/m}^3$) [6], making it highly sensitive to changes in water content. Even within this range, relatively small increases in water content can significantly raise the overall w/b , thereby impairing strength. Conversely, although reducing water content within the appropriate range lowers w/b , it also decreases PD under the same compaction conditions and may induce autogenous shrinkage during early-age curing, which can further reduce compressive strength [7–9]. Therefore, understanding the influence of water volume on the early-age strength of ZSC at a fixed PD is essential, particularly given the limited research on the independent roles of PD and water content.

Considerable efforts have been devoted to developing methods for determining the appropriate water content (by weight) of ZSC [10,11]. Two primary approaches are widely used: the method recommended by ACI 211 [6] and that outlined in the *Guide for Roller-Compacted Concrete Pavements* [12]. In the ACI 211 method, a preliminary water content is estimated from solid fraction within solids [13–15], followed by trial tests to refine and validate the practical value. By contrast, the *Guide* advocates a soil compaction approach that has gained broad acceptance in the academic community [16–20]. This method identifies the optimal water content as the volume required to achieve maximum dry density under a given compaction energy, since maximum dry density is directly associated with the highest compressive strength [21,22]. In practice, once the solid fractions with solids are fixed, mixtures with different water contents ranging from 5% to 8% of total mass (including water and all solids) are compacted using either the Modified Proctor (ASTM D1557) or Standard Proctor (ASTM D698) test [23,24]. The results are used to construct a moisture-density curve, and the water content at the peak dry density is designated as optimal. However, Das et al. [25] emphasized that the determination of optimal water content is strongly influenced by compaction energy, indicating that values obtained under laboratory conditions may not be directly transferable to field applications. In addition, when the cement fraction within the solids is relatively low, a higher optimal water content can increase the w/b , which may result in reduced compressive strength and is not considered in the soil compaction method. Therefore, it is essential to develop a new design approach that not only minimizes the number of trials needed to determine optimal water content but also balances the trade-off between increasing PD and the water-to-cement (w/c) ratio when adjusting water content.

Four compaction methods are commonly employed for concrete in laboratory settings: the Modified Proctor test, vibratory table, vibratory hammer, and gyratory compactor (GY) [26]. Among these, the GY exhibits a distinct compaction mechanism known as kneading compaction, in which shear stress is applied to the concrete mixture through simultaneous rotation and constant vertical pressure. Because interparticle attractive forces primarily resist compressive forces rather than shear stress, the applied shear facilitates particle sliding, enabling denser packing and reducing interparticle voids. Consequently, the GY typically achieves a higher PD than the other methods [27–30] and reaches the target PD more rapidly due to this shear-induced sliding effect [2,29]. Furthermore, the GY can automatically control specimen height, maintaining a consistent PD and improving reproducibility while minimizing human error [29]. In contrast, the other three compaction methods cannot directly control PD after compaction. Therefore, the GY is selected as the compaction technique in this study.

This study aims to investigate the role of water in the early-age compressive strength development of ZSC, providing guidance for optimizing water content design. Two mix designs with identical PD but different water volumes are first tested to evaluate strength variations, and a solid particle distribution model is developed to interpret the observed trends. Based on this model, a prediction method is proposed to avoid the detrimental effects of inappropriate water content and validated using a cement-sand system. The method is further extended to a three-component system comprising cement, sand, and ground granulated blast-furnace slag (GGBFS) to demonstrate its broader applicability. Finally, a new water content design approach incorporating the proposed prediction method

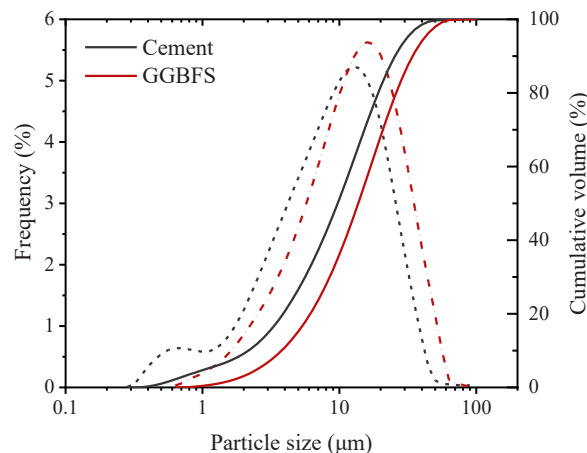


Fig. 1. Particle size distribution of cement and GGBFS.

is introduced, providing a practical framework for ZSC mix optimization.

2. Experimental program

2.1. Materials

The raw materials used for the preparation of ZSC include Portland cement CEM I 52.5 R (PC), GGBFS from Ecocem, and standard sand (S) that complies with European standard EN 196–1. The specific densities of cement, GGBFS, and sand are determined using a gas pycnometer (AccuPyc 1340 II) as 3.15 g/cm³, 2.81 g/cm³, and 2.65 g/cm³, respectively. The particle size distributions (PSD) of cement and GGBFS are analyzed using a laser diffraction analyzer (Malvern Mastersizer 2000®), as shown in Fig. 1.

2.2. Mix design

As noted earlier, the early-age compressive strength of ZSC is governed by the combined influence of PD and water content. To characterize the compaction behavior of ZSC, both PD and wet packing density (WPD) are introduced to calculate the corresponding values of each mix design using Eq. (1) and Eq. (2), respectively. PD describes how densely the solid particles are packed, while WPD represents how densely the entire mixture (water and solids) is packed.

$$\Phi_{PD} = \frac{V_{solids}}{V_{samples}} = \frac{\sum_{i=1}^n \frac{m_i}{\rho_i}}{h \bullet \pi \bullet D^2 / 4} \quad (1)$$

where h is the height of samples after compaction, which is 112 mm in this study; D is the diameter of samples after compaction (100 mm for all samples); m_i is the mass of solid component i ; n is the number of solid components; ρ_i is the density of the solid component.

$$\Phi_{WPD} = \frac{V_{solids} + V_{water}}{V_{samples}} \quad (2)$$

where V_{water} is the volume of added water.

As mentioned previously, ZSC requires compaction for shaping, and the gyratory compactor (GY) is selected for this purpose. The GY used in this study is equipped with a mold 170 mm in height and 100 mm in diameter; more detailed information about the equipment and the compaction process can be found in [2]. To investigate the effect of water volume on compressive strength independently of packing density (PD), PD must be kept constant. This requires specimens with the same solid volume but different water volumes to have the same height after compaction. Based on preliminary trials, cylindrical specimens with a height of 112 mm and a diameter of 100 mm are produced, corresponding to a total volume of 880 cm³. Two mixtures, Mixture 1 (M1) and Mixture 2 (M2), each with a fixed solid volume of 650 cm³ but varying water volumes, are designed, as shown in Table 1 and Fig. 2. The cement volume is set to 100 cm³ for M1 and 150 cm³ for M2.

2.3. Sample preparation and testing

Each specimen in every mix design is prepared independently, with each batch producing three specimens. After weighing the raw materials according to Table 1, the mixing process begins with a 1-min dry mixing stage. Water is then added, and mixing continues for an additional minute to obtain a homogeneous mixture. The fresh mixture is subsequently poured into the mold and compacted using the GY compaction device. Upon completion of compaction, the sample is demolded, immediately wrapped in plastic film to prevent the evaporation of free water, and then placed in a climate chamber maintained at 80% relative humidity and 35 °C for one day of curing, in order to simulate the curing conditions typically used in precast concrete plants. Subsequently, uniaxial unconfined compressive strength tests are performed using a hydraulic loading system. The compressive strength is calculated based on the maximum compressive force recorded during the test. A loading rate of 1 kN/s is applied when the compressive force is below 150 kN, and this rate is increased to 5 kN/s once the force exceeds this threshold.

Table 1
Mix design for investigating the effect of water volume.

Mix design	M1	M2
Cement (cm ³)	100	150
Sand (cm ³)	550	500
The total volume of solid particles (cm ³)	650	650
The sample volume after demolding (cm ³)	880	880
PD (%)	73.89	73.89
The water volume (cm ³)	85/90/95/105/115/125/135	120/130/140/150/160

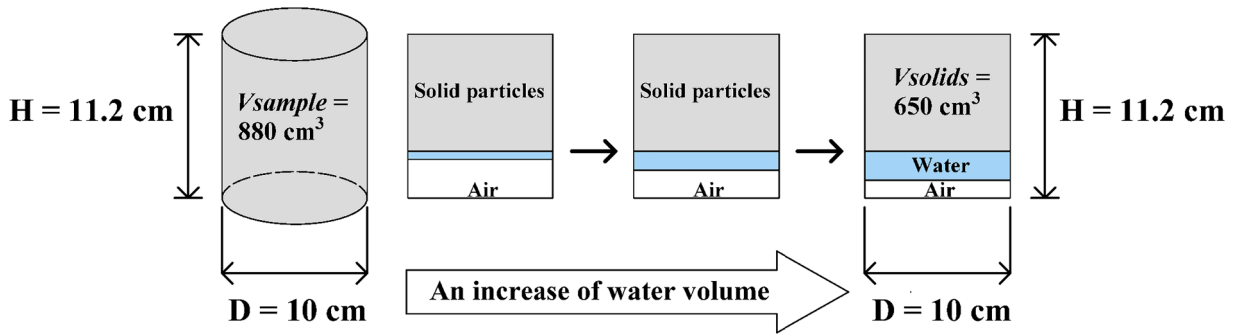


Fig. 2. Schematic illustration of increasing water volume under a fixed PD and constant sample volume.

3. Results and discussion

3.1. Compressive strength evolution results

Fig. 3 illustrates the relationship between compressive strength and the w/c ratio for M1 and M2. For M1, an increase in water volume from 85 cm³ to 95 cm³ leads to a rise in compressive strength from 12.1 MPa to 15.7 MPa, while the w/c ratio increases from 0.25 to 0.29. Beyond 95 cm³, however, compressive strength stabilizes, showing only slight fluctuations between 95 cm³ and 105 cm³ despite the continuous increase in w/c ratio. A similar trend is observed for M2: as the water volume increases from 120 cm³ to 140 cm³, corresponding to a rise in the w/c ratio from 0.25 to 0.30, compressive strength continues to increase. Yet, beyond 140 cm³, additional water does not yield further improvement in compressive strength.

The relationship between water volume and compressive strength during the flattening stage is evaluated using ANOVA for both M1 and M2. The p-values obtained are 0.70 and 0.98 for M1 and M2, respectively, both exceeding the 0.05 significance threshold. This confirms that there is no statistically significant variation in compressive strength within the flattening stage, which corresponds to water amounts of 95–135 cm³ for M1 and 140–160 cm³ for M2. Importantly, this strength development deviates markedly from conventional concrete behavior, where an increase in w/c ratio typically leads to a reduction in compressive strength [31–34]. This pronounced difference indicates that conventional explanations cannot account for the strength development observed in ZSC, motivating the need for a new model to capture the mechanisms governing its overall strength behavior.

3.2. A new model for explanation of early-age compressive strength

The compressive strength of concrete is primarily governed by the w/c ratio, the degree of compaction and the degree of hydration, under controlled conditions such as constant cement content, curing method, and temperature [31,35]. The w/c ratio influences strength by altering the spacing between cement particles: a higher water content increases particle spacing [35]. Although a higher w/c ratio can promote greater hydration, Abram's law states that the closer particle spacing associated with lower w/c ratios leads to

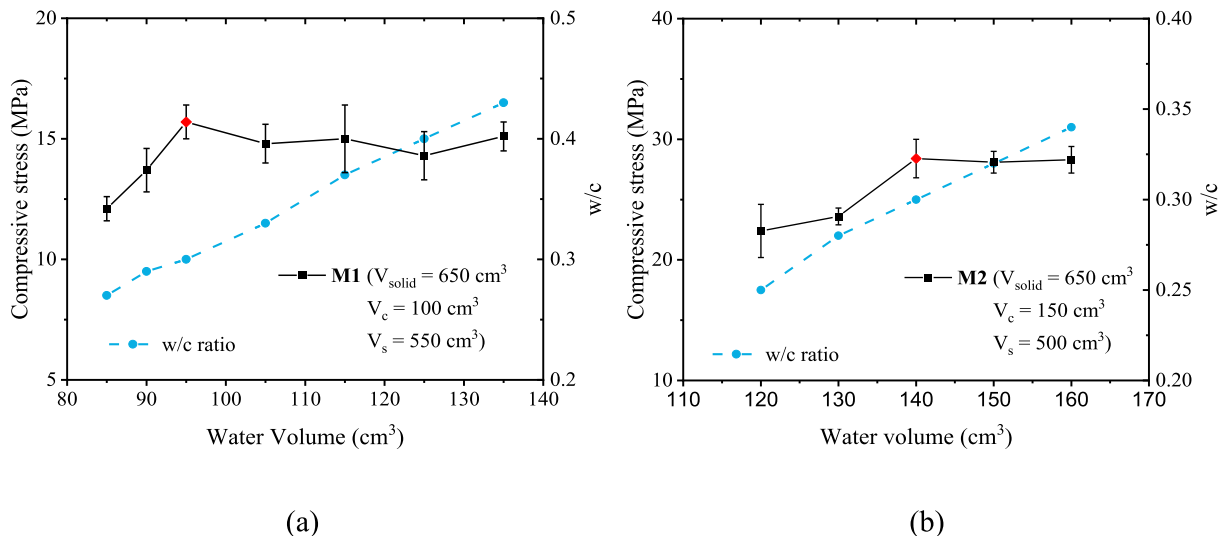


Fig. 3. Compressive strength and w/c of M1 (a) and M2 (b) with the increasing water volume.

higher compressive strength [36]. This is because closer spacing allows hydration products to form a denser load-bearing skeleton, while unhydrated cement particles remaining at low w/c ratios act as rigid inclusions that further enhance strength [35]. Based on this principle, the strengths of M1 and M2 would normally be expected to decrease with increasing w/c ratio. However, the experimental results reveal a distinctly different trend, indicating that the effect of water on cement particle distances in this system differs from conventional assumptions. This suggests that cement particle spacing must be explicitly considered.

The degree of compaction is defined as the ratio between the bulk density and the density of a fully compacted mix (i.e., free of entrapped air) [31]. Typically, increasing the degree of compaction increases both the PD and the WPD, thereby enhancing compressive strength. Previous studies have reported a linear relationship between PD and compressive strength [2,11]. Based on this relationship, mixtures M1 and M2, which have the same PD but different WPD values, would be expected to exhibit similar compressive strength. However, the experimental results in Section 3.1 show that compressive strength varies with WPD under the constant PD conditions, indicating that internal water volume influences compressive strength development. One possible explanation is related to the role of water in the degree of cement hydration, where a higher w/c ratio would promote a higher degree of hydration. Since a fixed PD implies that the total void volume (including both air and water) is preset in M1 and M2, increased hydration product formation could progressively fill the available void space, thereby contributing to strength development. However, numerous studies have shown that the degree of hydration at 1 day is largely insensitive to the w/c ratio [37–46]. Early hydration is rate-controlled and governed by the surface area of CsS exposed to water [46–49]. When the cement specific surface area is fixed, the available reactive surface area remains constant, leading to same hydration levels across mixes. Consequently, comparable amounts of hydration products are formed after 1 day of curing for mixtures with different water volumes.

Nevertheless, similar hydration levels and identical total void volumes after 1 day of curing do not necessarily result in identical compressive strength, as shown in Fig. 3. As discussed above, in conventional systems, increasing the w/c enlarges the spacing between cement particles, thereby reducing the density and connectivity of hydration products and ultimately lowering compressive strength. Accordingly, compressive strength would be expected to decrease with increasing w/c. However, the experimental trends observed in this study deviate from this expectation, suggesting that the evolution of cement particle spacing in ZSC with increasing w/c differs from conventional assumptions. The results indicate that cement particle spacing may remain approximately constant as w/c increases; under such conditions, the density and connectivity of hydration products would also remain similar, leading to comparable compressive strengths. A more detailed discussion of cement particle spacing is provided in Section 3.2.1.

Furthermore, even under the assumption of similar cement particle spacing, the compressive strengths of M1 and M2 with w/c ratios lower than 0.3 are lower than those with w/c ratios equal to or greater than 0.3. This difference can be primarily attributed to autogenous shrinkage. Previous studies have shown that autogenous shrinkage occurs when the water-to-binder ratio is below approximately 0.42 [7,8]. The w/c ratios of ZSC fall within this range, and the effect becomes more pronounced at a curing temperature of 35 °C, as elevated temperatures accelerate cement hydration. As hydration consumes pore water, negative pore-water pressure increases sharply, inducing volumetric shrinkage and microcracking in the interparticle regions between cement particles, thereby reducing compressive strength [9,50,51]. In addition, it has been reported that increasing the w/c ratio can delay the development of pore-water pressure associated with autogenous shrinkage, suggesting that, at a given curing age, a sufficiently high w/c ratio may mitigate strength reduction caused by early-age autogenous shrinkage [52]. Based on this analysis, a w/c ratio of approximately 0.3 appears to represent a transitional value in this system, beyond which the influence of autogenous shrinkage on compressive strength becomes less significant. This explains why mixtures with w/c ratios below 0.3 exhibit lower compressive strength compared with those at or above 0.3.

In summary, based on the above discussion, a new model incorporating both cement particle spacing and autogenous-shrinkage-induced interparticle cracking is proposed to explain the observed compressive strength development.

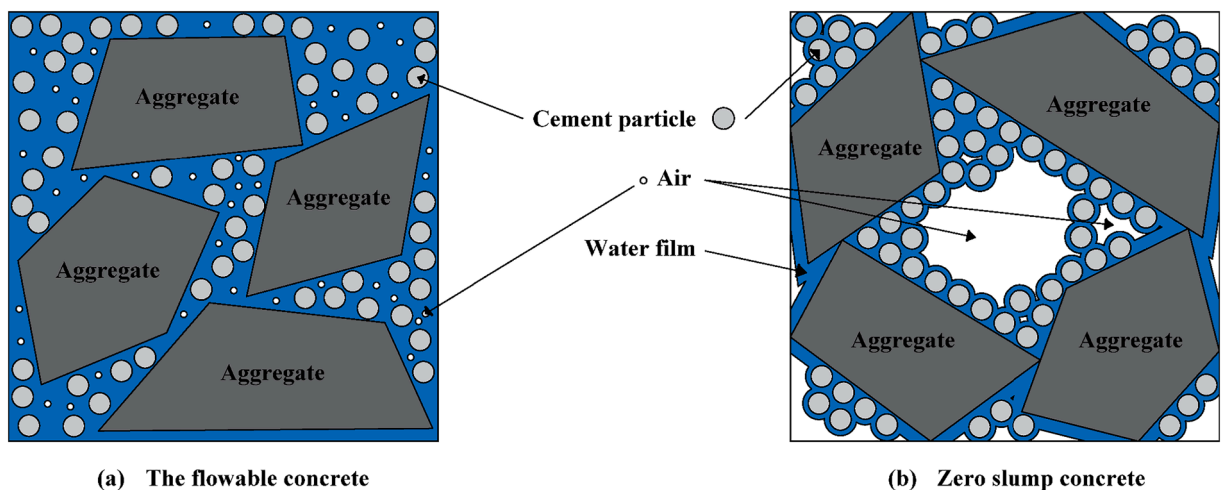


Fig. 4. Schematic illustration of particle distribution of the flowable concrete and ZSC.

3.2.1. Solid particle distribution model of compacted ZSC

Ideally, at a fixed sample volume, solid particles are uniformly distributed throughout the concrete, with water filling the remaining voids [2]. This model, however, applies only to flowable concrete, where sufficient water allows particles to move freely and achieve a uniform arrangement, as illustrated in Fig. 4(a). In contrast, for ZSC, the very low water content causes cement and aggregate particles to agglomerate during mixing, as shown in Fig. 5, indicating that a uniform particle distribution comparable to that of conventional concrete cannot be achieved. This occurs because cement particles flocculate and form a percolated network through colloidal interactions [53–55], while the low water content generates negative pore water pressure that pulls the particles together. Furthermore, since ZSC requires compaction for forming, the large aggregate particles form a solid skeleton through point-to-point contact, leaving the voids within this skeleton to be filled by smaller particles such as cement, as shown in Fig. 4(b). Therefore, to accurately describe the actual internal structure of compacted ZSC, a more realistic solid particle distribution model is built in this study.

In geotechnical engineering, studies on clay have shown that clay particles tend to clump together into “clay aggregates”, with water preferentially accumulating on particle surfaces [56–60]. When the water content exceeds that required for surface films, the surplus water resides in intra-aggregate pores, while the average particle distances remain constant due to strong attractive forces between particles [58]. Since fresh cement particles in water exhibit behavior analogous to clay, and given the limited literature on cement agglomeration under unsaturated conditions, it is reasonable to infer a comparable mechanism for cement particles. Specifically, cement particles are expected to agglomerate into “cement aggregates”, within which the average cement particle spacing remains approximately constant and the internal voids can be defined as intra-aggregate pores. Water initially forms thin films coating the cement particle surfaces, while additional water preferentially accumulates within the intra-aggregate pores. As mentioned earlier, “cement aggregates” tend to occupy the voids formed by the solid skeleton; however, their spatial distribution within these voids is non-uniform. In addition, owing to negative pore water pressure, cement agglomerates are drawn toward and preferentially adhere to the surfaces of the larger aggregate particles.

Accordingly, a solid particle distribution model that reflects the realistic particle arrangement in ZSC is established as follows: (a) cement particles are assumed to form agglomerates, hereafter referred to as “cement aggregates,” as illustrated in Fig. 6; and (b) at the macroscopic level, these cement aggregates accumulate within the voids of the solid skeleton and adhere to the surfaces of the larger aggregates, as shown in Fig. 4(b), consistent with the practical observation in Fig. 5. Although cement particles are angular and irregular in shape, their average interparticle spacing is assumed to remain constant. For modeling purposes, the particles are idealized as cycles to facilitate conceptual analysis.

It should be noted that as the water volume increases, water first adheres to the surfaces of solid particles and then extends into the pores between them. Within a certain range of water volume, the average distance between cement particles has the potential to remain unchanged due to the attractive forces acting among the particles, as shown in Fig. 7. In addition, after adequate compaction, the average cement particle distance can remain stable because the air within both inter-aggregate and intra-aggregate pores is readily expelled during compaction. However, two factors may cause these limits to be exceeded, resulting in an increase in the average cement particle distance. The first is the water dilution effect: once the intra-aggregate pores within the agglomerated structure are filled, any additional water causes the cement aggregates to expand in volume, thereby increasing the average distance between cement particles, as shown in Fig. 7. This phenomenon is analogous to that observed in geotechnical engineering, where, beyond the



Fig. 5. Fresh mixture after mixing.

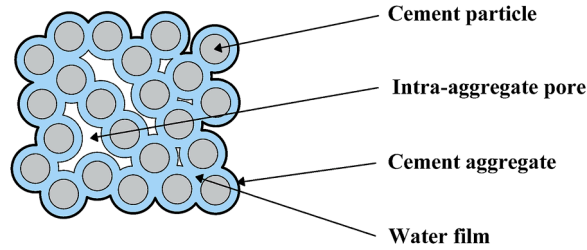


Fig. 6. Schematic illustration of the microstructure of cement aggregates formed by colloidal interactions and negative pore water pressure.

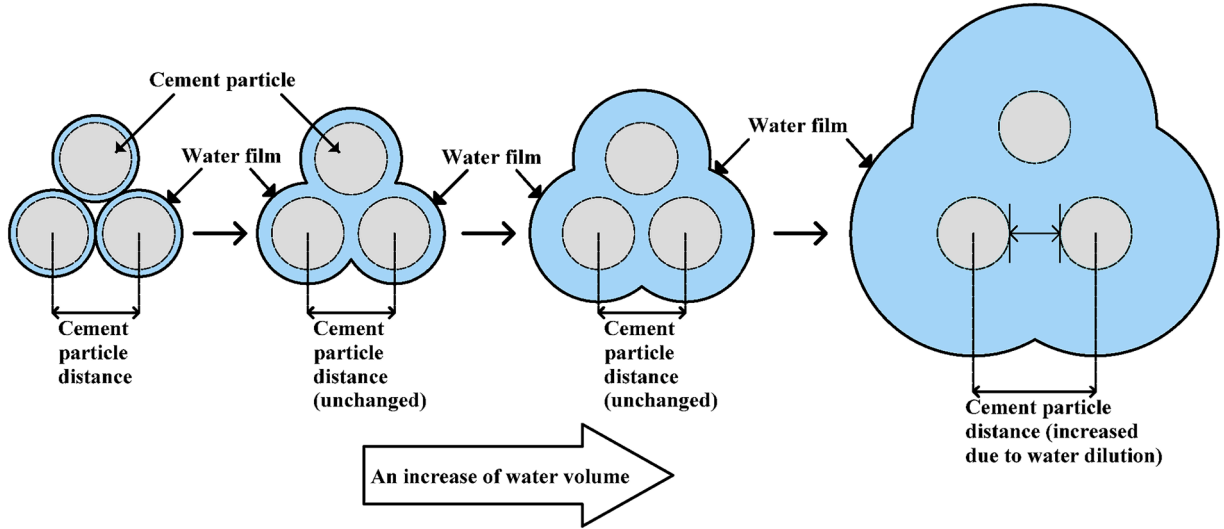


Fig. 7. Schematic illustration of increasing water volume. (The cement particle distance is defined as the center-to-center distance between particles.).

shrinkage limit, additional water induces expansion of the soil mass [25]. The second factor is the pore water pressure, which can also contribute to an increase in cement particle distances, as shown in Fig. 8. The GY compaction process involves the application of constant pressure from the top and bottom plates, followed by the generation of shear stress through the rotation of inclined molds around a fixed axis. A detailed description of the GY compaction method is provided in [2]. According to soil mechanics [25], the distribution of stress across a given cross section of the cement aggregates can be expressed by Eq. (3).

$$\sigma = \sigma' + u \quad (3)$$

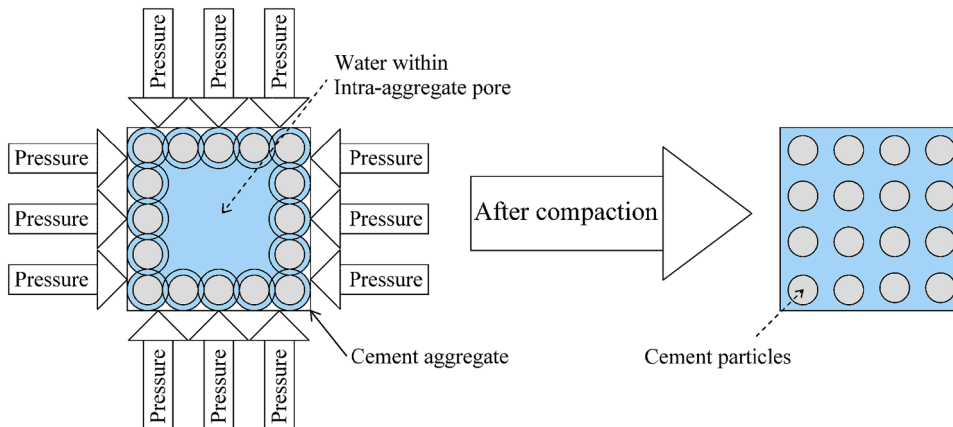


Fig. 8. Schematic of the effect of pore water pressure on the microstructure of cement aggregates.

where σ denotes the total external stress acting on the given cross section, σ' represents the effective stress, defined as the sum of all intergranular contact forces per unit cross-sectional area, and u is the pore water pressure within the same cross section.

During the early stage of compaction, intra-aggregate pores within the cement aggregates can still accommodate excess water. Therefore, no pore water pressure develops, and the solid skeleton bears the entire external applied stress. As compaction proceeds and the air pores within the cement aggregates are gradually eliminated, the continuous external pressure induces pore water pressure within the intra-aggregate pores, since water is nearly incompressible. In regions where cement aggregates and sand particles are densely packed and water drainage is restricted, the pore water pressure can increase until it approaches the total applied stress. At this point, intergranular contact forces vanish, leading to the disintegration of the solid skeleton and an increase in particle spacing. Moreover, liquefaction of the solid particles may even occur, allowing water to move freely out of the specimen while carrying fine particles, as observed in [61–64].

In summary, a solid particle distribution model is proposed to characterize cement particle packing in compacted ZSC, with the key features summarized as follows: (a) cement particles do not distribute uniformly but instead agglomerate into cement aggregates that adhere to the larger aggregates (e.g., sand in this study); and (b) the spacing between cement particles within cement aggregates may remain constant irrespective of the water volume, but can increase due to the effects of water dilution and pore-water pressure.

3.2.2. The mechanism behind the compressive strength development

In this section we aim to explain mechanism behind the development of compressive strength based on the proposed solid particle distribution model. The preceding discussion clearly elucidates that the compressive strength is simultaneously affected by cement particle spacing and autogenous-shrinkage-induced interparticle cracking. In term of cement particle spacing, the increasing cement particle spacing caused by water dilution and pore water pressure can reduce the compressive strength. In terms of autogenous shrinkage, below the specific threshold of w/c , the interparticle cracking caused by autogenous shrinkage cannot be prevented at the given curing age, resulting in the reduction in compressive strength. Since these two factors are coupled in influencing compressive strength, while the proposed model primarily describes cement particle spacing, the combined effects of these mechanisms are incorporated into the proposed model.

For simplification and conceptual clarity, in the following explanation of the mechanism, all the added water is assumed to form a film coating the solid constituents, including cement and aggregates (i.e., sand in this study), while all solid particles are idealized as spheres. Under these assumptions, the average water film thickness (WFT) within the sample can be calculated as:

$$t = \frac{V_w}{A_{overall}} \quad (4)$$

where V_w is the volume of water, $A_{overall}$ is the total surface area of solid particles and t is the average thickness of water film for the mixture;

$$A_{overall} = \sum_{i=1}^n A_i \quad (5)$$

where A_i is the surface area of a given component corresponding to a specific single PSD;

$$A_i = V_i \cdot T_i \quad (6)$$

where T_i is conversion coefficient (m^{-1}) between volume and surface area of a given component and V_i is the volume (m^3) of that component;

$$T_i = \sum_{j=1}^n P_j \cdot \frac{6}{R_j} \quad (7)$$

where P_j is PSD distribution of a given component and R_j is the corresponding diameter of spherical particles of that size, assuming all particles are idealized as spheres.

It should be noted that Eq. (4) can be used to calculate the WFT of each component when both the water volume coating the component and its total surface area are known.

Both cement particle spacing and autogenous shrinkage are governed by the water volume, which influences compressive strength by affecting the interactions between cement particles. Furthermore, besides the increase in cement particle spacing caused by pore water pressure, the increase in cement particle spacing resulting from water dilution and the mitigation of autogenous shrinkage can both be directly related to the WFT of cement particles. Therefore, it is further assumed that only the water film coating the cement particles contributes to the mitigation of shrinkage and the increase in cement particle spacing, whereas the water film coating the aggregates does not participate in either process. As discussed in Section 3.2.1, pore water pressure occurs at a higher compaction degree when water must resist the applied external pressure. Therefore, WPD, which represents how densely the entire mixture (water and solids) is packed, is used as an indicator for preventing pore water pressure. Based on these assumptions and analyses, the development of compressive strength is related to the WFT of cement particles and the WPD of the specimens after compaction. Accordingly, the development of compressive strength can be interpreted in terms of the WFT surrounding cement particles (Fig. 9) and the WPD, as outlined below:

Case 1: When pore water pressure does not influence cement particle spacing (Fig. 9(a))

- (1) $WFT < D_{optimal}$ while the interparticle distances remain constant ($D_{optimal}$ corresponds to the lowest WFT at which the water coating the cement particles is sufficient to mitigate shrinkage, resulting in maximum compressive strength.): At comparatively low water content, the consumption of water during hydration leads to an increase in negative pore water pressure, which induces cracking within the cement aggregates. The formation of these microcracks reduces the compressive strength of the ZSC. Consequently, supplying additional free water mitigates shrinkage by alleviating the negative pore water pressure, resulting in an increase in compressive strength.

	Without pore water pressure influence		
WFT	$WFT < D_{optimal}$	$D_{optimal} < WFT < D_{dilution}$	$WFT > D_{dilution}$
Autogenous shrinkage	Cracking	Mitigating	Mitigating
Cement particle distances	Constant	Constant	Increasing
Compressive strength development with increasing cement particle WFT			

(a)

	With pore water pressure influence					
	$WPD > WPD_{max}$ occurs within $D_{optimal} < WFT < D_{dilution}$			$WPD > WPD_{max}$ occurs before $WFT = D_{optimal}$		
WFT	$WFT < D_{optimal}$	$D_{optimal} < WFT < D_{dilution}$		$WFT < D_{optimal}$	$D_{optimal} = WFT$	$D_{optimal} < WFT$
WPD	$WPD < WPD_{max}$	$WPD < WPD_{max}$	$WPD > WPD_{max}$	$WPD > WPD_{max}$	$WPD > WPD_{max}$	$WPD > WPD_{max}$
Autogenous shrinkage	Cracking	Mitigating	Mitigating	Cracking	Mitigating	Mitigating
Cement particle distances	Constant	Constant	Increasing	Increasing	Increasing	Increasing
Compressive strength development with increasing cement particle WFT					 Peak point	

(b)

Fig. 9. Schematic illustration of the effects of the WFT of cement particles and pore water pressure on compressive strength development: (a) without the influence of pore water pressure, and (b) with the influence of pore water pressure.

- (2) $WFT = D_{optimal}$ while the interparticle distances remain constant: Sufficient free water on the cement particle surfaces slows the rise of negative pore water pressure, allowing its detrimental effect to diminish and the concrete to achieve its maximum compressive strength.
- (3) $D_{optimal} < WFT < D_{dilution}$ while the interparticle distances remain constant ($D_{dilution}$ corresponds to the WFT beyond which the water coating cement particles is sufficient to increase their interparticle spacing.): In this range, the increase in negative pore water pressure is already mitigated due to the sufficient water supply, while the additional water does not yet enlarge the spacing between cement particles. Consequently, the compressive strength of ZSC remains approximately constant.
- (4) $WFT > D_{dilution}$, resulting in increased interparticle distances: When the WFT exceeds $D_{dilution}$, excessive water increases the spacing between cement particles. This larger spacing reduces the density and connectivity of hydration products, ultimately leading to a decrease in compressive strength.

Case 2: When pore water pressure influences cement particle spacing (Fig. 9(b))

- (1) $WPD > WPD_{max}$ occurs within $D_{optimal} < WFT < D_{dilution}$ (WPD_{max} corresponds to the WPD at which the pore water pressure caused by external compaction is sufficient to increase cement particle spacing.): In this case, a flattening stage still exists, similar to that without the influence of pore water pressure, and the onset of the flattening stage occurs when the WFT of cement particles equals $D_{optimal}$. However, the termination of the flattening stage occurs earlier at the water volume where the increase in pore water pressure enlarges the spacing between cement particles, leading to a decrease in compressive strength.
- (2) $WPD > WPD_{max}$ occurs before $WFT = D_{optimal}$: When the WFT of cement particles is below $D_{optimal}$, the mitigation of negative pore water pressure due to increased WFT can compensate for the strength reduction caused by greater interparticle spacing. Consequently, the compressive strength can continue to increase until the WFT reaches $D_{optimal}$. However, once the WFT exceeds $D_{optimal}$, further increases in cement particle spacing caused by the pore water pressure lead to a decline in compressive strength.

The compressive strength development described in Section 3.1 can be interpreted in light of the above mechanism. As the water volume approaches the threshold $D_{optimal}$, corresponding to approximately 95 cm³ for M1 and 140 cm³ for M2, the detrimental effect of the negative pore water pressure progressively decreases until it disappears. The corresponding compressive strength follows a similar rising trend. Beyond these thresholds, the negative pore water pressure no longer affects the concrete, resulting in a flattening stage in compressive strength for M1 and M2 beyond 95 cm³ and 140 cm³ of water, respectively. Furthermore, no subsequent decline in strength is observed after this flattening stage, indicating that the water dilution effect has not occurred.

4. A method to predict the water volume range corresponding to the flattening stage of compressive strength development

4.1. Establishment of the prediction method based on the proposed model

According to the proposed mechanism in Section 3.2.2, at a curing age of one day, compressive strength with increasing water volume exhibits either a peak point or a flattening stage where the strength remains at its maximum level, depending on whether pore water pressure influences cement particle spacing. When the water volume is too low such that the WFT of cement particles is below $D_{optimal}$, the negative effects of autogenous shrinkage cannot be fully mitigated, and therefore the compressive strength cannot reach its maximum value. In addition, when the water volume is sufficiently high that the WFT of cement particle exceeds $D_{dilution}$, or when pore water pressure affects particle spacing, the spacing between cement particles increases, resulting in compressive strength values lower than the maximum. Therefore, accurately predicting the water volume range corresponding to the maximum compressive strength is essential for the rational design of ZSC to prevent the detrimental effects of inappropriate water content at a given curing age. In this section, a method is proposed to predict the range of water volumes corresponding to the maximum compressive strength, based on the solid particle distribution model and the relationship among WFT, autogenous shrinkage, and cement particle spacing.

As discussed in Section 3.2.2, the water volume range corresponding to the maximum compressive strength may be affected by pore water pressure. When pore water pressure does not influence cement particle spacing, the water volumes at the onset and termination of the range can be calculated, based on the proposed model, by summing the water volumes coating each component of the mixture at the corresponding stage. Furthermore, the water volume coating each component can be calculated by multiplying the total surface area of that component by its WFT. Therefore, for predicting the appropriate water volume with the same materials, and in addition to the assumptions stated in Section 3.2.2, the WFT of each component is assumed to be a constant intrinsic value at both the onset and termination of the flattening stage. Accordingly, for cement particles, $D_{optimal}$ for mitigation of the autogenous shrinkage and $D_{dilution}$ for preventing water dilution, corresponding to the onset and termination of the flattening stage, respectively, are treated as intrinsic constants. It should be noted, however, that different cement sources, fineness levels, or curing temperatures may influence these values through their effects on hydration kinetics and autogenous shrinkage development. Meanwhile, it is assumed that the aggregates absorb only a small and constant amount of water, irrespective of the total water volume in the mixture, indicating that the WFT of the aggregates remains constant. Based on these assumptions, and in the absence of pore water pressure, the water volume range for different mix designs using the same constituent materials can be estimated as:

$$V_w = \sum_{i=1}^n (t_i \bullet V_i \bullet T_i) \quad (8)$$

where T_i is conversion coefficient (m^{-1}) between volume and surface area of a given component, t_i denote the WFT of that component and V_i is the volume (m^3) of that component.

Consequently, accurately determining the WFT of each component from the corresponding water volume is essential for applying Eq. (8).

When pore water pressure influences cement particle spacing, the water volume range corresponding to the maximum compressive strength depends on the stage at which pore water pressure begins to affect cement particle spacing. When the effect of pore water pressure occurs within $D_{\text{optimal}} < \text{WFT} < D_{\text{dilution}}$, the water volume at the onset of the flattening stage remains the same as that without the influence of pore water pressure, whereas the water volume at the termination of the flattening stage corresponds to the water volume at which WPD_{max} is reached. When the effect of pore water pressure occurs before $\text{WFT} = D_{\text{optimal}}$, only a peak point exists in the compressive strength development. In this case, the corresponding water volume can be calculated using Eq. (8), with the WFT of each component corresponding to the onset of the flattening stage. It should be noted that pore water pressure, which increases cement particle spacing, is influenced by external compaction and the stiffness of the solid skeleton. Therefore, WPD_{max} , which represents the WPD required to prevent pore water pressure, cannot be regarded as a constant intrinsic value for all mix designs but should instead be determined based on the specific practical conditions.

In summary, the above discussion analyzes how to consider the onset and termination of the water volume range corresponding to the maximum compressive strength, both with and without the influence of pore water pressure. Based on this analysis, four important parameters are required to determine the water volume range: D_{optimal} , D_{dilution} , the constant WFT of aggregates and WPD_{max} . Since the determination of WPD_{max} has already been discussed, the next step is to derive the WFT of each component using Eq. (8), which will be discussed in the following paragraph.

The overall process for determining the WFT of each component can be summarized as follows: first, the water volumes corresponding to the onset and termination of the flattening stage are derived from the compressive strength results and then substituted into Eq. (8) to solve the WFT of each component. It should be noted that when more than two solid components are involved in Eq. (8), the components are classified into two categories: binders and aggregates. This classification is adopted because the WFT of aggregates is considered constant, and the water volume required to satisfy this WFT is governed solely by their PSD. Furthermore, since SCM particles exhibit properties similar to those of cement particles, all binder components agglomerate into “binder aggregates,” within which the cementitious particles are uniformly distributed [65,66]. This agglomerated structure implies the existence of a water distribution relationship governing the WFT among the binder aggregates. It further indicates that when any individual component within the binder aggregates is first affected by water dilution or pore water pressure, the entire binder aggregate is influenced, resulting in a reduction in compressive strength. Therefore, this relationship must first be established to enable the subsequent derivation of the WFT of each individual binder component under practical conditions. Meanwhile, the equation for predicting the termination of the flattening stage should employ the D_{dilution} of the component that is first affected by water dilution, together with the corresponding WFTs of the other components. An example application is provided in Section 4.3.

To further illustrate the application of the proposed prediction methodology, a binary sand-cement system is considered to derive the equation for predicting the onset of the flattening stage in the absence of pore water pressure. In this case, Eq. (8) can be simplified and rewritten as:

$$V_w = t_s \bullet V_s \bullet T_s + t_c \bullet V_c \bullet T_c \quad (9)$$

where V_s and V_c represent the volumes of sand and cement, respectively; t_s and t_c denote the WFT for sand and cement, respectively; T_s and T_c are conversion coefficient (m^{-1}) between volume and surface area for sand and cement, respectively; and V_w represents the water volume.

In Eq. (9), two unknown parameters need to be determined: the WFTs of sand and cement. Therefore, two different mix designs with varying proportions of sand and cement are employed to derive these parameters, which can be expressed as follows:

$$V_{w1} = t_s \bullet T_s \bullet V_{s1} + t_c \bullet T_c \bullet V_{c1} \quad (10)$$

$$V_{w2} = t_s \bullet T_s \bullet V_{s2} + t_c \bullet T_c \bullet V_{c2} \quad (11)$$

where V_{w1} and V_{w2} represent the volumes of water in Mixture 1 and Mixture 2, respectively, at the onset of the flattening stage; V_{s1} and V_{s2} denote the volumes of sand in Mixture 1 and Mixture 2, respectively; and V_{c1} and V_{c2} denote the volumes of cement in Mixture 1 and Mixture 2, respectively. In addition, the water volume at the onset of the flattening stage is identified as the first point where the difference in compressive strength is within 5% compared to the next point.

The product $T_i \bullet t_i$ can be treated as a constant when the same materials are employed. By solving Eq. (10) and Eq. (11), the product $T_i \bullet t_i$ can be derived as follows:

$$t_c \bullet T_c = \frac{(V_{w1} \bullet V_{s2} - V_{w2} \bullet V_{s1})}{(V_{c1} \bullet V_{s2} - V_{s1} \bullet V_{c2})} \quad (12)$$

$$t_s \bullet T_s = \frac{(V_{w2} \bullet V_{c1} - V_{w1} \bullet V_{c2})}{(V_{c1} \bullet V_{s2} - V_{s1} \bullet V_{c2})} \quad (13)$$

By substituting Eq. (12) and Eq. (13) into Eq. (9), the equation for the onset of the flattening stage for a mix design containing cement and sand can be obtained:

$$V_w = \frac{(V_{w2} \bullet V_{c1} - V_{w1} \bullet V_{c2})}{(V_{c1} \bullet V_{s2} - V_{s1} \bullet V_{c2})} \bullet V_s + \frac{(V_{w1} \bullet V_{s2} - V_{w2} \bullet V_{s1})}{(V_{c1} \bullet V_{s2} - V_{s1} \bullet V_{c2})} \bullet V_c \quad (14)$$

4.2. Validation of the proposed prediction method

4.2.1. Experimental validation of the predicted onset of the flattening stage

By solving Eq. (12) and Eq. (13) using water volume at onset of flattening range, corresponding to 95 cm³ and 140 cm³ of water for M1 and M2, respectively, the products $T_s \bullet t_s$ and $T_c \bullet t_c$ are obtained as 0.008 and 0.908, respectively. Substituting these values into Eq. (14) yields Eq. (15) as follows:

$$V_w = 0.008 \bullet V_s + 0.908 \bullet V_c \quad (15)$$

In Eq. (15), the term $0.008 \bullet V_s$ for sand represents the amount of water absorbed by the aggregates, which does not contribute to mitigation of autogenous shrinkage or the increase in the cement particle spacing, while the term $0.908 \bullet V_c$ for cement represents the lowest water volume required for cement particles to mitigate autogenous shrinkage. In this section, Eq. (15) is validated by predicting the onset of flattening stage across different mix designs employing the same materials as those presented in Section 3.1.

Five different mix designs with varying PD are developed to validate Eq. (15). By substituting V_s and V_c from each of the five mix designs into Eq. (15), the corresponding onset values are calculated and are presented in Table 2. To simplify the experimental procedure, the predicted onset values for each mix design are rounded up, as shown in Table 2. During preliminary trials, specimens with a solid volume below 625 cm³ are found to be more susceptible to damage during transfer to the climate chamber due to insufficient green strength after demolding. Therefore, specimens with solid volumes less than 625 cm³ are excluded from this study.

Fig. 10 illustrates the compressive strength development of five different mix designs with increasing water volume. In these figures, the red points indicate the compressive strength corresponding to the predicted onset of the flattening stage, while the grey shaded areas represent the flattening stage of compressive strength. It can be observed that three distinct stages exist, which is consistent with the analysis presented in Section 3.2.2. Before the red points, which mark the onset of the flattening stage, the compressive strength exhibits an increasing trend. Once the water volume reaches the red point, the compressive strength enters a flattening stage, during which further increases in water volume do not result in significant changes in strength. An exception is observed in Fig. 10(e), where no apparent flattening stage is detected within the range of 130 cm³ to 160 cm³ of water. This phenomenon is attributed to pore water pressure, and a detailed analysis will be presented in Section 4.2.2. Following the flattening stage, the compressive strength begins to decline. Despite the discrepancy in Fig. 10(e), all red points consistently correspond to the onset of the flattening stage. Therefore, it can be concluded that the calculation of the onset of the flattening stage using Eq. (15) is valid across different PD in the absence of pore water pressure.

4.2.2. New insights from the validation process

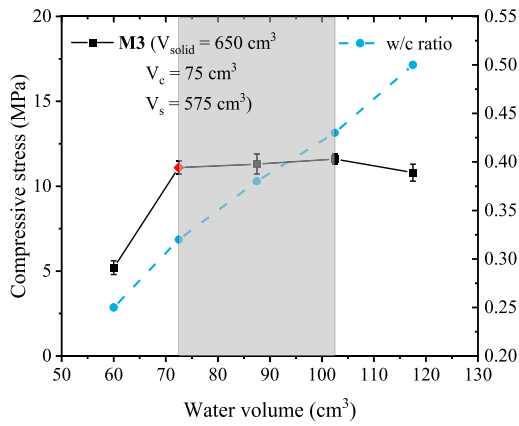
Two key insights emerge from the validation process. The first concerns the combined roles of PD and water volume in compressive strength development. Table 3 shows that the compressive strength corresponding to the onset of the flattening stage increases as the PD rises from 73.89% to 79.58%, which aligns with the conventional trend in concrete where compressive strength increases with a higher PD. However, as shown in Fig. 10, for the same PD, the compressive strength development across all mix designs is dependent on the water volume within the sample. Therefore, it can be concluded that PD and water volume jointly influence compressive strength.

The second insight concerns the decreasing trend in compressive strength development. Unlike the trend observed in Section 3.1, a decrease in compressive strength is observed across all mix designs, as shown in

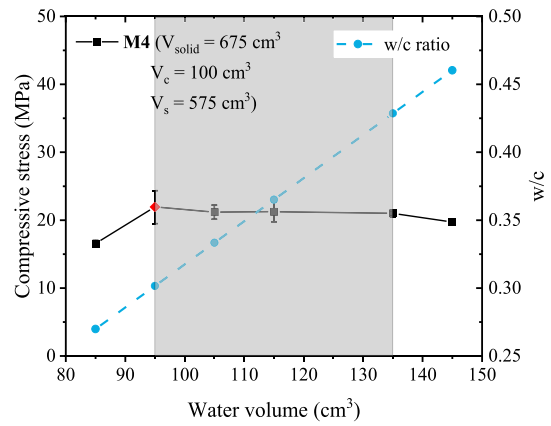
Fig. 10. As discussed in Section 3.2, this decrease can be attributed to the increasing distance between cement particles, which reduces both the density and connectivity of hydration products, thereby lowering the compressive strength. The increase in cement particle spacing is caused by two main factors, as described in Section 3.2.

Table 2
Different mix designs for validation.

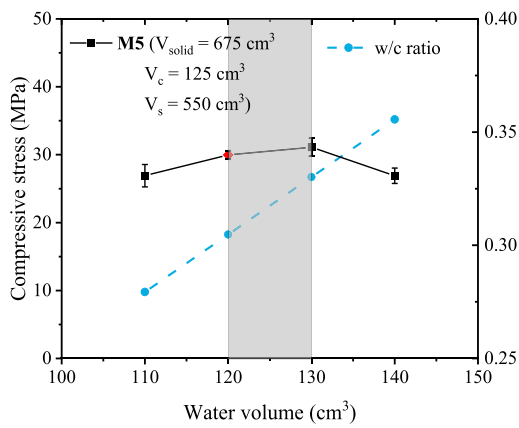
Mix design	M3	M4	M5	M6	M7
Cement (cm ³)	75	100	125	100	150
Sand (cm ³)	575	575	550	600	550
The total volume of solid particles (cm ³)	650	675	675	700	700
The sample volume after demolding (cm ³)	880	880	880	880	880
PD (%)	73.89	76.74	76.74	79.58	79.58
Predicted onset of the flattening stage (cm ³)	72.5	95.2	117.7	95.4	140.4
The actual water volume (cm ³)	72.5	95	120	95	140



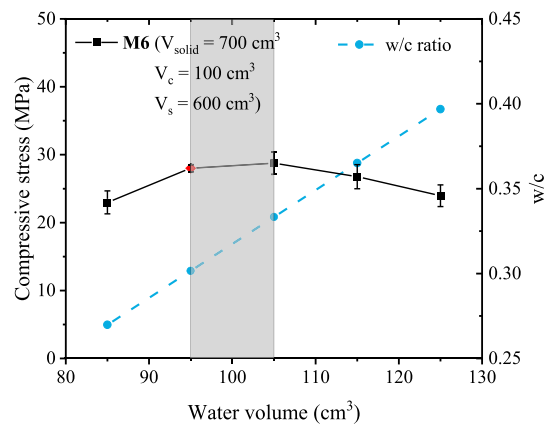
(a)



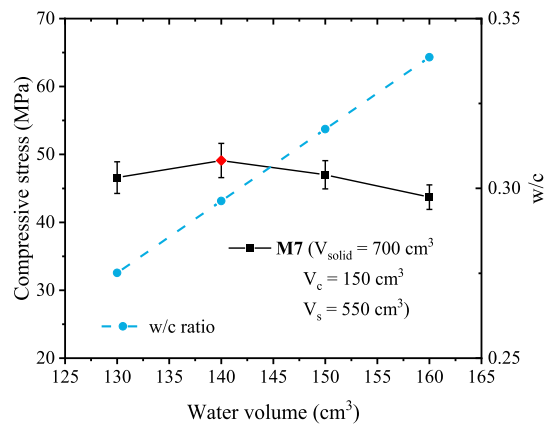
(b)



(c)



(d)



(e)

Fig. 10. Compressive strength development of M3, M4, M5, M6, and M7 with the increasing water volume. The grey shaded areas represent the flattening stage of compressive strength.

Table 3
Compressive strength corresponding to the onset of flattening stage.

	Sand volume increases			Cement volume increases		
Mix design	M1	M4	M6	M1	M5	M7
Cement (cm ³)	100	100	100	100	125	150
Sand (cm ³)	550	575	600	550	550	550
The total volume (cm ³)	650	675	700	650	675	700
PD (%)	73.89	76.74	79.58	73.89	76.74	79.58
Compressive strength (MPa)	15.7	21.9	28.0	15.7	30	49.1

The first factor is attributed to water dilution, with the detailed mechanism discussed in Section 3.2.1. Cement particles mixed with water exhibit certain similarities to clay, suggesting that when the WFT reaches a specific threshold D_{dilution} , the intra-aggregate pores within the cement aggregates become fully saturated. Beyond this point, any additional water absorbed by the cement aggregates cannot be accommodated within the pores, leading to swelling of the aggregates and an increase in the average distance between cement particles. As a result, the compressive strength begins to decline.

Since the conversion coefficient (T_c) of cement particles between volume and surface area can be calculated by substituting the PSD of cement (Fig. 1) into Eq. (7), the WFT development of cement particles for M3, M4, M5, M6, and M7 at different water amounts can be calculated using Eq. (4) and the results are plotted in Fig. 11. The points around 0.68 μm of WFT for all mix design correspond to the onset of the flattening stage shown in Fig. 10, indicating that their WFTs reach D_{optimal} . For M3 and M4, the strength reduction occurs when the water contents reach 117.5 cm³ and 145 cm³, respectively, which correspond to points beyond 1 μm . As discussed in Section 3.2.1, when the WFT of cement exceeds D_{dilution} , the compressive strength begins to decline due to the increased cement particle spacing induced by the water dilution effect. This indicates that the WFT values of cement at these points exceed D_{dilution} . Considering that D_{dilution} is an intrinsic material property, a WFT of 1 μm is suggested as the threshold marking the onset of the water dilution effect. This value should be regarded as a reference only, as it lies within a range where compressive strength varies. A more accurate threshold should be determined following the experimental protocol established in this study. In contrast, for M5, M6, and M7, although the WFTs remain below 1 μm , the compressive strength still decreases, indicating that the strength reduction is not caused by dilution effects but is instead attributable to pore water pressure.

Secondly, as discussed in Section 3.2.1, pressure caused by compaction increases the pore water pressure within cement aggregates that change the microstructure, resulting in increased cement particle distances within cement aggregates. For cement aggregates, during the compaction, the inter-aggregate pores and intra-aggregate pores both are squeezed out from the specimen. At the beginning, there still exist intra-aggregate pores inside the cement aggregate where the trapped water can move and thus there is no pore water pressure. When there are less air pores inside cement aggregates for movement of water and the left intra-aggregate pores are completely occupied by water, the continuous pressure on the cement aggregates can incur the pore water pressure within the intra-aggregate pores. Since some part of specimen are stacked closely by cement aggregates and aggregates (sands) and there is no room for water draining outside cement aggregates, the pore water pressure would increase to the extent that the total stress exerted from the compaction is equal to. At this point, pore water pressure can break down binding force among cement particles that thus are suspended into the water. In the suspended state, the cement particle distances would increase, as shown in Fig. 8.

Since WPD can serve as an indicator of pore water pressure, some data on WPD are presented in Table 4 using Eq. (2). The data indicate that when the WPD reaches or exceeds 92.65%, a decline in compressive strength is observed. This suggests that even though pores still exist, as indicated by the WPD, the influence of pore water pressure becomes significant. At this stage, portions of the cement aggregates, particularly those located at the center of the specimen, may be compacted into a liquefied suspension, leading to structural weakening. This mechanism accounts for the decreasing compressive strength observed in M4, M5, M6, and M7. It is important to highlight that, based on the above analysis, the strength reduction in M4 can be attributed to a combination of two factors: dilution caused by excessive water and structural damage induced by pore water pressure.

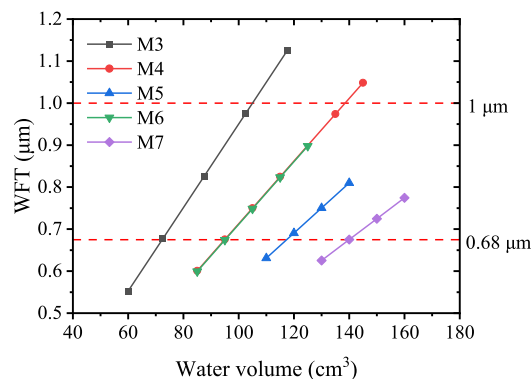


Fig. 11. WFT of M3, M4, M5, M6, and M7.

Table 4

WPD of M4, M5, M6, and M7.

Mix design	M4		M5		M6		M7		
Cement (cm ³)	100		125		100		150		
Sand (cm ³)	575		550		600		550		
The total volume (cm ³)	675		675		700		700		
Water (cm ³)	135	145	130	140	105	115	130	140	150
WPD (%)	92.08	93.22	91.51	92.65	91.51	92.65	94.36	95.49	96.30
Compressive strength (MPa)	21	19.7	31.1	26.9	28.7	26.8	46.6	49.1	47

However, for M7, when the water volume increases from 130 cm³ to 140 cm³, corresponding to WPD values of 94.36% and 95.49%, respectively, the compressive strength still shows potential for improvement. A noticeable decrease in strength occurs only when the water volume exceeds 150 cm³. This behavior arises because, although the pore water pressure at 130 cm³ has already disrupted the particle network, the water film coating cement particles is still insufficient to mitigate autogenous shrinkage. At this stage, the mitigation of autogenous shrinkage through additional water can offset the strength reduction caused by particle disruption. As more water is added, autogenous shrinkage is further alleviated, and compressive strength increases until the WFT reaches its optimal value, corresponding to the onset of the flattening stage, where the strength peaks. Beyond this point, excess water enhances pore water pressure and increases particle spacing, resulting in a marked reduction in compressive strength.

In summary, the proposed model in Section 3.2 adequately explains the reduction in compressive strength observed in M3-M7, which is attributed to the increase in cement particle spacing caused by either water dilution or pore water pressure. For water dilution, a WFT of 1 μ m is recommended as D_{optimal} for the cement used in this study. For pore water pressure, a WPD of 92.65% is suggested as WPD_{max} for the mix designs tested in this study.

4.3. Applicability of the prediction method to SCM-modified binders

4.3.1. Application analysis of the prediction method

The prediction method for the onset of flattening stage has been validated for a two-component pure cement system (Section 4.2). However, its applicability to more sustainable ZSC, such as SCM-modified mixtures, remains uncertain. As SCM-modified ZSC is widely used in precast plants to reduce cement consumption and associated CO₂ emissions, this section presents an application example using a blended system of cement and GGBFS to demonstrate the practical relevance of the proposed method. Other SCMs, such as fly ash, silica fume, and calcined clay, may also be incorporated within the same framework following the procedure presented in this study.

To facilitate demonstration of the proposed method in SCM-modified ZSC, only one additional component, GGBFS, is introduced into the mix design presented in Section 4.2. Therefore, Eq. (8) can be extended and reformulated as:

$$V_w = t_s \bullet V_s \bullet T_s + t_c \bullet V_c \bullet T_c + t_G \bullet V_G \bullet T_G \quad (16)$$

where V_G , T_G and t_G represent the volume of GGBFS, the conversion coefficient (i.e., the volume-based specific surface area, SSA, of GGBFS), and the average thickness of the water film surrounding GGBFS particles, respectively.

As discussed in Section 4.1, four key parameters are required to determine the water volume range: D_{optimal} , D_{dilution} , the constant WFT of aggregates, and WPD_{max} . For convenience in applying Eq. (16), the product $T_i \cdot t_i$ can be treated as a single parameter when the same materials are used. Since the values of $T_i \cdot t_i$ for cement particles corresponding to D_{optimal} and D_{dilution} , the $T_i \cdot t_i$ of sand, and WPD_{max} have already been derived in Section 4.2, only the $T_i \cdot t_i$ values of GGBFS particles corresponding to D_{optimal} and D_{dilution} need to be determined here. According to the assumption that WFT at the onset and termination is an intrinsic constant, the samples attain their maximum compressive strength at the onset of the flattening stage when the water films surrounding the cement and GGBFS

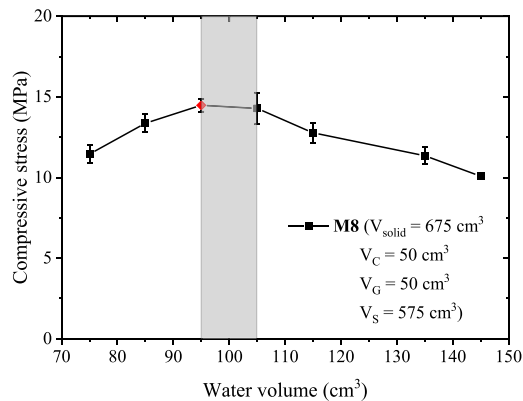


Fig. 12. Compressive strength development of M8 with the increasing water volume.

particles reaches their corresponding WFT. Therefore, the water volume coating GGBFS can be obtained by subtracting the water required for sand and cement from the total water volume. This approach enables the derivation of the unknown parameter $T_G \cdot t_G$ corresponding to $D_{optimal}$ at the onset of the flattening stage. As discussed in Section 4.1, determining the $T_G \cdot t_G$ corresponding to $D_{dilution}$ at the termination of the flattening stage requires establishing a water distribution relationship between cement and GGBFS, which is presented in a later section.

Based on above discussion, a new mix design (M8) is developed to determine both $T_G \cdot t_G$ and the water distribution relationship. This mix design comprises 50 cm³ of cement, 50 cm³ of GGBFS, and 575 cm³ of sand. Specimens with varying water volumes are prepared to investigate the development of compressive strength. After determining $T_G \cdot t_G$ and the water distribution relationship using M8, equations for predicting the onset and termination of the flattening stage are constructed and subsequently validated in a later section.

4.3.2. Validation of the prediction method for SCM-modified binders

As shown in Fig. 12, the onset of the flattening stage corresponds to a water volume of 95 cm³, whereas its termination occurs at 105 cm³. By solving Eq. (16) using the onset value of flattening stage for M8, $T_G \cdot t_G$ is determined to be 0.904. Substituting $T_s \cdot t_s$, $T_c \cdot t_c$ and $T_G \cdot t_G$ into Eq. (16) yields Eq. (17), which can be used to predict the onset of the flattening stage as follows:

$$V_w = 0.008 \cdot V_s + 0.908 \cdot V_c + 0.904 \cdot V_G \quad (17)$$

As discussed in Section 4.3.1, a water distribution relationship between cement and GGBFS is required to derive $T_G \cdot t_G$ corresponding to $D_{dilution}$ at the termination of the flattening stage. This relationship is analyzed below. Compared to M4, M8 replaces 50 cm³ of cement with 50 cm³ of GGBFS, resulting in equal volumes of cement and GGBFS (50 cm³ each). However, as shown in Fig. 12, the onset of the flattening stage for M8 remains at 95 cm³ of water, consistent with that of M4, indicating that equal volumes of GGBFS and cement are coated by equivalent amounts of water. This may be attributed to the capillary forces within the water film. Although cement particles have a higher affinity for water than GGBFS, the continuous water phase within the “binder aggregates” formed by cement and GGBFS allows the capillary forces to distribute the water film evenly over the surfaces of both cement and GGBFS particles. Based on this observation, the water allocation relationship between cement and GGBFS can be assumed using Eq. (18) and Eq. (19), respectively, as follows:

$$V_w^c = (V_w - t_s \cdot V_s \cdot T_s) \cdot \frac{V_c}{(V_c + V_G)} \quad (18)$$

$$V_w^g = (V_w - t_s \cdot V_s \cdot T_s) \cdot \frac{V_G}{(V_c + V_G)} \quad (19)$$

where V_w^c and V_w^g denote the volume of water coating cement and GGBFS, respectively.

These equations are then employed to predict the termination point of the flattening stage. If the termination point is successfully predicted in the following analysis, the assumed water allocation relationship is thereby validated. It should be noted, however, that in systems containing ultrafine SCMs or highly absorptive particles, local water redistribution may occur due to differences in surface energy, pore structure, or absorption kinetics. Under such conditions, the assumption of uniform water allocation may become less accurate, and a weighted or non-uniform water allocation model may be more appropriate.

After establishing the water distribution relationship, the next step is to derive $T_G \cdot t_G$ corresponding to $D_{dilution}$ at the termination of the flattening stage and subsequently construct the equation for predicting the termination of the flattening stage. In M8, based on the application of Eq. (4), Eq. (18), and Eq. (19), WFT of cement is calculated as 0.75 μm and 0.82 μm at water amounts of 105 cm³ and 115 cm³, respectively. Correspondingly, the WFT of GGBFS is determined to be 1.38 μm and 1.51 μm under the same conditions. Since the WFT of cement does not reach 1 μm, the threshold at which cement interparticle distances begin to increase, the observed decrease in compressive strength between 105 cm³ and 115 cm³ of water suggests that the reduction beyond 105 cm³ may be attributed to the water dilution effect in GGBFS. Furthermore, at this stage, the WPD is 89.81%, indicating no significant pore water pressure. Therefore, 1.38 μm is regarded as $D_{dilution}$ of the GGBFS, beyond which the water film coating the GGBFS particles becomes sufficient to increase the particle spacing within the binder aggregates, leading to the decrease in the compressive strength.

As discussed in Section 4.1, the termination of the flattening stage caused by water dilution in SCM-modified binders depends on the component that is first affected by water dilution, since the components agglomerate into binder aggregates. In this case, when the water film coating the GGBFS particles becomes sufficient to increase the particle spacing between GGBFS and neighboring particles,

Table 5

The predicted value at the onset and termination of the flattening stage for M9.

Mix design	M9
Cement (cm ³)	30
GGBFS (cm ³)	70
Sand (cm ³)	575
The total volume (cm ³)	675
Predicted onset of the flattening stage (cm ³)	95
Predicted termination of the flattening stage (cm ³)	105

the average particle spacing within the binder aggregates increases, leading to the reduction in compressive strength. Therefore, when substituting the WFTs of cement and GGBFS into Eq. (16) to predict the termination of the flattening stage, the WFT of GGBFS (1.38 μm) and the corresponding WFT of cement (0.75 μm) are used to derive Eq. (20), which predicts the dilution point as follows:

$$V_w = 0.008 \bullet V_s + 1.006 \bullet V_c + 1.006 \bullet V_G \quad (20)$$

A mix designs (M9) is developed to validate Eq. (17) and Eq. (20). By substituting the volumes V_G , V_c and V_s from the mix design into Eq. (17) and Eq. (20), the water volumes at the onset and termination of the flattening stage are calculated, as presented in Table 5.

Fig. 13 illustrate the compressive strength development of M9 with increasing water volume. In this figure, the red and blue points represent the compressive strengths corresponding to the onset and termination of the flattening stage, respectively, while the grey shaded areas denote the flattening stage of compressive strength. It can be observed that the red and blue points closely match the onset and conclusion of the flattening stage. Therefore, it can be concluded that the calculations for the onset and termination of the flattening stage using Eq. (17) and Eq. (20), respectively, are valid. In addition, the derived values at the onset of the flattening stage (i. e., 0.008 for sand and 0.908 for cement in Eq. (8)) are shown to be transferable to other mix designs composed of the same raw materials (see Eq. (17)), thereby demonstrating that the assumption that the WFT of each component is an intrinsic and constant material property is reasonable.

5. A new water content mix design method and its potential limitations

As introduced in Section 1, the soil compaction method (the mainstream mix design method for ZSC) aims to determine the optimal water content that yields the maximum dry density, based on the principle that achieving maximum dry density leads to maximum compressive strength. However, this methods does not account for the coupled effect of PD and water volume on compressive strength. Although an increase in PD generally enhances compressive strength, this study finds that, an inappropriate water content can reduce the 1-day compressive strength of ZSC due to autogenous shrinkage, water dilution, and pore water pressure. To address these limitations, a new water content mix design method for ZSC based on the prediction method is proposed, with the detailed procedure presented in the following section.

(1) Determination of the material properties

Material properties of the raw materials need to be determined: (a) apparent density and PSD of all raw materials; (b) D_{optimal} and D_{dilution} for all cementitious materials, as well as the constant WFT of aggregates; (c) the water distribution relationship between cement and SCMs; (d) WPD_{max} to prevent the detrimental effect caused by pore water pressure. These parameters can be determined using the procedures described in Section 4 and can subsequently be applied to the design of other mixes employing the same materials.

(2) Mix design processes

It should be noted that the proposed mix design method focuses solely on optimizing the water volume fraction to mitigate its detrimental effects. Therefore, the design of solid component volume fractions is beyond the scope of this study. Readers are referred to [2,11] for detailed guidance on determining the volume fractions of solid components. Accordingly, in the subsequent description of the proposed mix design procedure, the volume fractions of each solid component relative to the total solid volume are assumed to be known.

After determining the material properties, the overall mix design process can be summarized as follows:

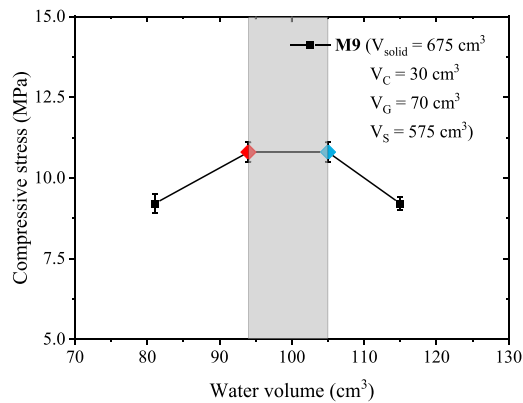


Fig. 13. Compressive strength development of M9 with the increasing water volume. The grey shaded areas represent the flattening stage of compressive strength.

- (a) Calculate the volume of each solid component per unit volume of 1 m^3 , based on the known volume fraction of each component relative to the total solid volume as follows:

$$V_{\text{total solid volume}} = \sum_{i=1}^n (V_{\text{solid},i}) = 1 \text{ m}^3 \quad (21)$$

$$V_{\text{solid},i} = P_i^{\text{solid}} \bullet V_{\text{total solid volume}} \quad (22)$$

where $V_{\text{total solid volume}}$ represents the total solid volume (equal to 1 m^3), including both cementitious materials and aggregates; P_i^{solid} and $V_{\text{solid},i}$ denote the volume fraction of a given solid component relative to the total solid volume and the volume of that solid component, respectively.

- (b) Select the WFT (t_i) for the binder solid components within the range between D_{optimal} and D_{dilution} , and then substitute the product $T_i \cdot t_i$ of each component into Eq. (8). The first requirement for selecting t_i is to ensure sufficient workability for compaction, so that the compacted ZSC can achieve the preset dimensions under the given compaction conditions. The second requirement is that the WPD of the compacted ZSC specimen should not exceed WPD_{max} . However, if the WPD exceeds WPD_{max} when $t_i = D_{\text{optimal}}$, the WFT for the binder solid components should be fixed at D_{optimal} .
- (c) Compute the required water volume V_w by substituting the $V_{\text{solid},i}$ into Eq. (8), and then calculate the volume fractions of all components relative to the total volume (including solids and water) as follows:

$$P^i = \frac{V_i}{V_w + V_{\text{total solid volume}}} \quad (23)$$

where P^i represents the volume fraction of a given component relative to the total volume, and V_i denotes the volume of that component.

- (d) Compute the mass of each components per unit volume of 1 m^3 as follows:

$$m^i = \rho_i \bullet P^i \bullet 1 \text{ m}^3 \quad (24)$$

where ρ_i represents the density of a given component, and m^i denotes the mass of that component per unit volume of 1 m^3 .

This study proposes a novel mix design method that optimizes water volume to achieve maximum compressive strength at 1-day curing. The proposed mechanism, involving cement particle spacing, autogenous shrinkage, water dilution, and pore water pressure, is grounded in compressive strength measurements and theoretical analysis. However, these mechanistic explanations represent conceptual inferences rather than directly experimentally verified phenomena. Specifically, the attribution of strength improvement at low water volumes to the mitigation of autogenous shrinkage, and the subsequent strength reduction to increased cement particle spacing or pore water pressure effects, are proposed as plausible interpretations consistent with the observed data, but have not been independently confirmed through microstructural or in-situ measurements. In addition, the proposed method can reduce the number of experimental iterations required for optimization and improve transferability across mixtures using the same raw materials, compared with conventional empirical trial-and-error approaches, offering improved efficiency and predictive capability.

Several limitations of the proposed model should be acknowledged. First, the prediction equations have been validated within a specific range of mix compositions, and the boundaries of cement content within the solid components for which these equations remain valid have not yet been fully established, warranting further investigation. Second, the mechanistic model does not account for all potentially contributing factors, such as hydration kinetics and temperature effects, which may influence the relationship between water volume and compressive strength under different conditions. Third, the methodology is currently applicable only to cement-based systems, including those incorporating different aggregate types and SCMs. Although chemical admixtures were not investigated in the present study, the applicability of the proposed framework to systems containing admixtures requires further validation. Furthermore, how water volume influences alkali-activated materials at a fixed packing density remains an open question requiring dedicated research. Fourth, the current framework has been developed primarily for 1-day compressive strength, where particle spacing, water distribution, and autogenous shrinkage strongly influence strength development. At later ages, continued hydration and microstructural densification are expected to become increasingly dominant, and therefore the applicability of the proposed framework may require further validation and refinement.

Future work should aim to validate the proposed mechanisms through direct experimental evidence, such as autogenous shrinkage measurements, or microstructural imaging, and to extend the model's applicability to a broader range of binder systems and curing conditions.

6. Conclusions

This study investigates the role of water in the early-age compressive strength development of zero-slump concrete (ZSC). A solid particle distribution model is proposed to explain the underlying mechanism of compressive strength development. Based on this model, a water prediction method is developed and experimentally validated. Subsequently, a new water content mix design approach is proposed using the developed method. Based on the findings of this study, the following conclusions can be drawn:

- (1) The compressive strength development of ZSC is influenced by both the PD and the water volume. For a given PD, the strength development is governed by the water volume within the ZSC and typically progresses through three distinct stages: an initial increasing stage, followed by a flattening stage, and finally a decreasing stage.
- (2) A solid particle distribution model of compacted ZSC is proposed to clarify the mechanism of compressive strength development at a constant PD under increasing water volume. The model demonstrates that the strength is jointly governed by the interparticle distances of cement and the magnitude of autogenous shrinkage. Before the flattening stage, additional water progressively reduces autogenous shrinkage while the interparticle distances remain unchanged, leading to a continuous increase in strength. During the flattening stage, autogenous shrinkage is sufficiently mitigated and further water addition does not alter particle spacing, resulting in a flattening stage. Beyond this stage, the decline in strength is attributed to enlarged interparticle distances induced by pore water pressure or water dilution.
- (3) Building on the solid particle distribution model, a prediction method is developed to mitigate the detrimental effects of water volume, including autogenous shrinkage, water dilution, and pore water pressure. Validation using a pure cement system composed of cement and sand shows that the prediction method reliably predicts the onset of the flattening stage across all mix designs, while the proposed model can well explain the strength evolution.
- (4) The prediction method can be extended to binder systems containing multi-phases (i.e. cement and GGBFS in this study), demonstrating its broader applicability. By incorporating the water allocation relationship between cement and GGBFS, the method enables accurate prediction of the entire flattening range using parameters derived from previous experiments. This confirms that the WFT of each component can be treated as an intrinsic and constant material property, and that the derived values are transferable to other mix designs formulated with the same raw materials.
- (5) Building upon the prediction method, a new mix design method for designing water content is developed to prevent the detrimental effects of autogenous shrinkage, water dilution and pore water pressure. The core procedure can be summarized as follows: (a) Determine the material properties of each solid component; (b) Select the water film thickness (t_i) for the binder components in accordance with practical requirements to calculate the corresponding water volume; and (c) Based on the calculated water volume, determine the mass of each component per unit volume.

CRediT authorship contribution statement

Xuan Ling: Investigation. **Jinyang Li:** Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Qingliang Yu:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **H.J.H. Brouwers:** Writing – review & editing, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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