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Review

A Review on the Use of Self-Curing Agents and Its Mechanism in High-Performance Cementitious Materials

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Abstract: Self-cured concrete is a type of cement-based material that has the unique ability to mitigate the loss rate of water and increase the capacity of concrete to retain water compared to conventional concrete. The technique allows a water-filled internal curing agent to be added to the concrete mixture and then slowly releases water during the hydration process. Many researchers have studied the composition of self-curing concrete using different materials such as artificial lightweight aggregate (LWA), porous superfine powders, superabsorbent polymers (SAP), polyethylene glycol (PEG), natural fibers, and artificial normal-weight aggregate (ANWA) as curing agents. Likewise, physical, mechanical, and microstructure properties, including the mechanisms of curing agents toward self-curing cement-based, were discussed. It was suggested that adopting self-curing agents in concrete has a beneficial effect on hydration, improving the mechanical properties, durability, cracking susceptibility behavior, and mitigating autogenous and drying shrinkage. The interfacial transition zone (ITZ) between the curing agent and the cement paste matrix also improved, and the permeability is reduced.

Keywords: high-performance concrete; self-curing; curing agents; mechanism; interfacial transition zone

1. Introduction

Curing is a process of maintaining the rate and the extent of moisture loss within a proper temperature in concrete during cement hydration and reduces water evaporation [1–4]. Curing allows continuous hydration of cement until achieving its potential strength and durability. However, it is critical to ensure that the moisture condition is appropriate; otherwise, the hydration of cement virtually ceases due to the relative humidity within the capillaries falling below 80% [1,5,6]. If hydration ceases, sufficient calcium silicate hydrate (C-S-H) cannot be developed [7,8], which disrupts the development of dense microstructure and the refined pore structure within the cement matrices allowing the ingress of deleterious agents into the concrete. These subsequently lead to poor quality of concrete, such as causing plastic shrinkage cracks, poorly formed hydrated products, finishing issues, and other surface defects [4,9,10].

Previous studies have reported various methods to prevent moisture loss during concreting like spraying or fogging the surface of newly cast concrete with water [1,11–14], applying wet surface covering [3,13,14], and water ponding which is suitable for horizontal surfaces [13–15]. Other methods mentioned include membrane curing, which retains the water within the concrete to maximize the potential hydration [3,10,13,14], steam [11,16–18], and leaving formwork in place [1,15]. Nevertheless, the accelerated curing methods such as microwave curing [19–21], direct electric curing [22–24], and infrared curing [25] are used in the application of heat on fresh concrete to promote rapid cement hydration by securing early-age strength of concrete. However, a more common feature of all existing curing techniques is frequently applied to the surface of the concrete. If the capillary porosity in the concrete is disconnected during the curing process, moisture is unable to penetrate the entire depth of the concrete, limiting the effectiveness of the curing process.

Therefore, a new approach of self-curing concrete has been introduced [26,27]. Self-curing or internal curing concrete can be defined as cement-based material having additional water capacity during the curing regime for the hydration process [28]. The practice of self-curing is a feasible technique that can supply more water to concrete towards more effective cement hydration and decrease self-desiccation. The following sections of this study present a review of the techniques which have been studied in self-curing agent reported by researchers, including its mechanism.

2. Mechanism of Hydration of Conventional Concrete

The addition of water to ordinary Portland cement (OPC) powder initiates the cement hydration reactions instantly. This series of chemical reactions leads in the cement paste setting and hardening. Within a few minutes, needle-like crystals of calcium sulfoaluminate hydrate, notably ettringite, develop. After a period of time, ettringite converts into monosulfate hydrate [22]. Two hours after the cementation process begins, large prismatic crystals of calcium hydroxide (CH) and tiny calcium silicate hydrates (C–S–H) fill the voids formerly filled by water and hydrated cement particles (as shown in Equations (1)–(6)). Therefore, calcium silicate hydrate, calcium hydroxide, and calcium sulfoaluminate are the three primary components of hydrated cement paste. Calcium silicate hydrate is the primary hydration product, contributing to almost 60% of the volume of solids. It is composed of a layer of sponge-like structures with a huge surface area (500 m^2/g). The ultimate strength of the product is largely owing to the development of C-S-H and is principally due to van der Waals physical adhesion forces. Calcium hydroxide is the second most prevalent component, contributing to approximately 25% of the total. Compared to C–S–H, it is composed of massive plate-like crystals with a lower surface area [22,25]. It contributes to the reduction of van der Waal forces and is relatively soluble in comparison to C–S–H, making the concrete reactive to acidic solutions. Calcium sulfoaluminate plays a small part in the cementitious structure properties by almost 15% solid volume. Chemical resistance of the cementitious final product to sulfate attack is an issue, owing to the existence of the monosulfate hydrate. Figure 1 shows electron microscopic images of hardened cement paste after hydration.

$$2\,\mathrm{Ca_3SiO_5} + 7\,\mathrm{H_2O} \leftrightarrow \mathrm{Ca_3Si_2O_3(OH)_8} + 3\,\mathrm{Ca(OH)_2} \tag{1}$$

$$2\,\mathrm{Ca_2SiO_4} + 5\,\mathrm{H_2O} \leftrightarrow \mathrm{Ca_3Si_2O_3(OH)_8} + \mathrm{Ca(OH)_2} \tag{2}$$

$$\mathrm{Ca_4Al_2Fe_2O_{10}} + 7\,\mathrm{H_2O} \leftrightarrow \mathrm{Fe_2O_3} + \mathrm{Ca_3Al_2(OH)_{12}} + \mathrm{Ca(OH)_2} \tag{3}$$

$$\mathrm{CaO} + \mathrm{H_2O} \leftrightarrow \mathrm{Ca(OH)_2} \tag{4}$$

$$\mathrm{Ca_3Al_2O_6} + 3\,\mathrm{CaSO_4 \cdot 2H_2O} + 26\,\mathrm{H_2O} \leftrightarrow [\mathrm{Ca_3Al(OH)_6 \cdot 12H_2O}]_2(\mathrm{SO_4}) \cdot 32\mathrm{H_2O} \tag{5}$$

$$\begin{gathered}[\mathrm{Ca_3Al(OH)_6 \cdot 12H_2O}]_2 \cdot (\mathrm{SO_4})_3 \cdot 2\mathrm{H_2O} + \mathrm{Ca_3Al_2O_6} + 4\,\mathrm{H_2O} \leftrightarrow \\ 3\,[\mathrm{Ca_2Al(OH)_6 \cdot 2H_2O}]_2\mathrm{SO_4} \cdot 2\mathrm{H_2O}\end{gathered} \tag{6}$$

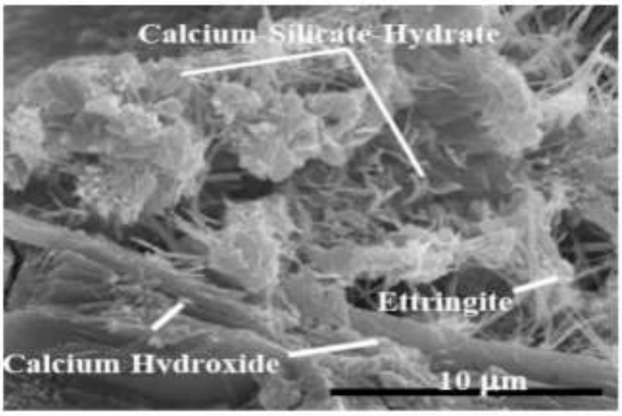

Figure 1. Electron microscopic images of hardened cement paste after hydration [13].

3. Self-Curing Agent and Mechanism in Cementitious Materials

Self-curing technology or internal curing has gained popularity within the concrete community research field. The concept of self-curing concrete or mortar is to reduce the evaporation of water in concrete and improve the water retention capacity in concrete [27–30]. As a result, the technique has been readily introduced where water-filled internal curing agents acting as reservoirs are added to the concrete mixture which will gradually release water during hydration and evaporation process [31–34], as illustrated in Figure 2. High-performance concrete (HPC) mixtures were initially developed given the growing issues regarding concrete durability [35,36] and due to the use of lower water-cementitious (w/c) material ratios, in addition to chemical admixtures and supplementary cementitious material (SCMs). Measuring the extent of hydration in the cementitious system is a key indicator that leads towards achieving the good performance of the concrete [37]. Low w/c ratio concrete mixtures, less than 0.42, are unable to fully hydrate the cement in the mixture due to insufficient water [1]. Therefore, the benefit of self-curing concrete from absorbed moisture in porous aggregate was discovered to solve the problem relating to insufficient water in HPC mixtures by providing extra water to replace that which was depleted during the process of cement hydration.

Many researchers have investigated self-curing concrete composition using different materials as curing agents, such as porous aggregate, for example lightweight aggregate (LWA) [38–41], porous superfine powders [42–45], artificial normal-weight aggregate [46–48], chemical curing agents, for example superabsorbent polymers [49–53] and polyethylene glycol [54–56], and natural fibers [33,57,58]. The following sub-sections explain the mechanism and properties of self-curing concrete using different curing agents.

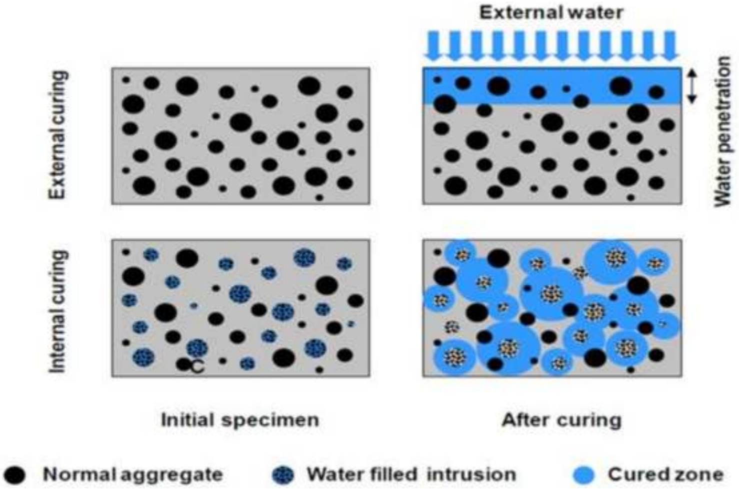

Figure 2. Illustration of the differences between self-curing and external curing [59].

Porous aggregate is frequently associated with poor concrete quality. However, when utilized in wet conditions, the aggregate might benefit the concrete since the water absorbed by the aggregate is slowly released into the already-hardened cement paste, continuing the hydration process. As a result, concrete properties such as increased strength and decreased drying shrinkage will be improved. The water movement is caused by the humidity gradient between the aggregate that is high and the cement paste that is low. According to [28] schematic diagram of the mechanism of self-curing concrete depicted as Figure 3. Self-curing, also known as autogenous curing or internal curing, enables curing "from the inside out", which is achieved by introducing a pre-saturated component as an internal curing agent. The curing agent is spread uniformly throughout the matrix and acts as a reservoir for internal water. The water within the curing agent has not involved in the chemical reaction until a humidity gradient forms during an initial hydration phase. On [29], it was illustrated that the self-curing process occurs as shown in Figure 4. Water is transported from the curing agent to un-hydrated cement by the driving forces of capillary suction, vapor diffusion, and capillary condensation for supporting continuous hydration. As result, chemical shrinkage and self-desiccation due to low w/b can be significantly reduced.

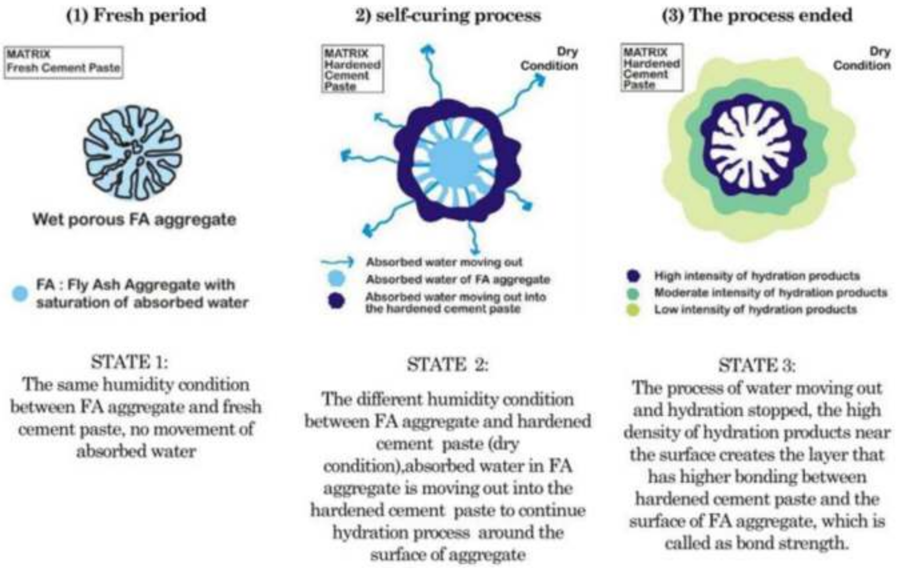

Figure 3. The mechanism of self-curing concrete [28].

3.1. Artificial Lightweight Aggregate (LWA)

Prewetted lightweight aggregates have often been used as internal reservoirs in which a system of capillary pores in cement paste is formed during hydration, and as soon as the relative humidity (RH) decreases (due to hydration and drying), a humidity gradient develops [35,60–62]. The migration of water in concrete based on the law of fluid flow and the system's law of capillary attraction is illustrated in Figure 5. As observed in the figure, the radius of pores in cement paste (r(t)) is smaller than the pores in LWA (Ra). The pores of the cement paste by capillary suction absorbs the water from the LWA due to difference in vapor pressure and transports the water to the drier cement paste, where a reaction with the un-hydrated cement occurs [35,62–64]. The un-hydrated cement particles, hydrated to form hydration products, reduce the size of the pores, enabling the pores to continue absorbing the water from the LWA. This process continues until all the water from LWA has been transported to the cement paste, creating a self-curing mechanism.

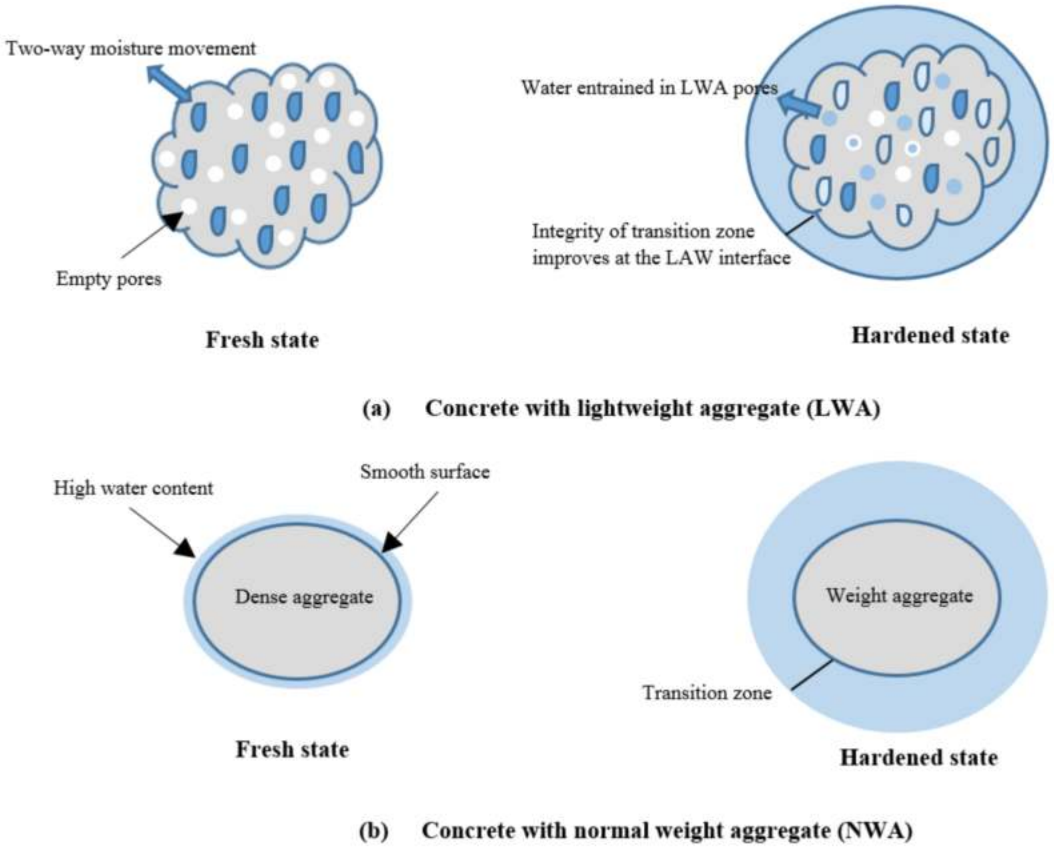

Figure 4. The contact zone under internal curing and normal curing.

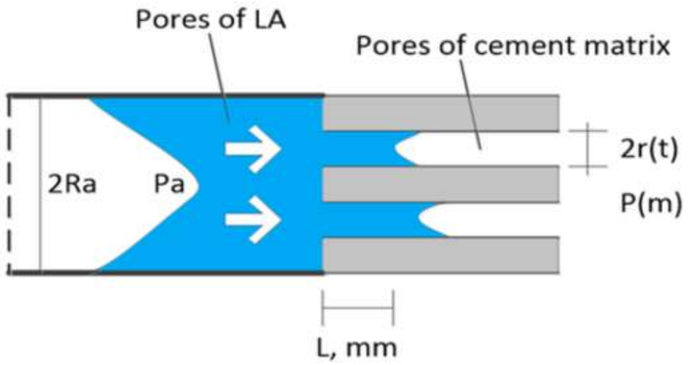

Figure 5. Model illustrating the movement of water in cement-based materials, incorporating self-curing with r(t) < Ra [64].

Among the various features found in LWA, it has been shown to have high porosity and absorption capacity with the added benefit of supplying curing water internally [38,65,66]. Moreover, due to contain of porosity, the density of LWA is less than that of artificial NWA. The saturated-surface dried density of LWA is reported to be below 2000 kg/m^3 [65,67–71]. However, water absorption of porous LWA depend on the pore structures. The minimum water absorption above 5% by mass of LWA is required as recommended by ASTM C1761/C1761M [72–74]. LWA can be in the form of coarse and fine aggregate and the more common aggregates used as a curing agent in self-curing concrete, which are natural-based, are expanded shale [75,76], expanded clay (LECA), [38,42,65,70,77–80] and pumice [68,81,82]. Whereas the curing agent from by-product materials, often studied by researchers, is bottom ash [4,69,70,83–86].

3.2. Porous Superfine Powders

Porous superfine powders are small particles with a large specific surface area and a mesoporous structure. It can absorb the aqueous phase, enabling water supply for the hydration process in the cementitious material [32,87]. Porous superfine powders possess nanometre-size pores, for instance, cenosphere [43,88–90], rice husk ash (RH) [44,45,91,92], and biochar [93,94]. Generally, the particle size of porous superfine powders ranges between 5 µm and 10 µm, which is much smaller compared to SAP particles and LWA, where the pore size ranges between 4 nm and 10 nm. Only if the pore size of cement paste is smaller than superfine powders' pore size will the water be released into the cement paste, in which the hydration process occurs. In addition, the application of porous superfine powders capable of slowing down the internal RH (self-desiccation) in UPHC significantly reduces its autogenous shrinkage [32,44,95]. According to the Kelvin equation [96], the capacity of water saturation would respond to changes in humidity betwixt 75% and 98%, whereas the pore size range corresponds to a change in RH of around 75 to 98%. It is assumed that the water stored in the mesopores will slowly release its water when the internal RH in concrete drops below 98% to compensate for self-desiccation during hydration. By using the concept of protected paste volume [97], it revealed that cement paste should be closed to the internal curing water reservoir so that the absorbed water could be penetrated. Thus, cement paste is protected from self-desiccation by the absorbed water. To achieve this, the curing agent particle size should be as small as possible [32,98].

3.3. Artificial Normal Weight Aggregate (ANWA)

Waste material in the construction industry such as ceramic [48,99,100] and recycled concrete waste [101–104] have the potential as water reservoirs in self-curing concrete given their ability to absorb water due to its porosity. Zou et al. [105] mentioned that the SSD density of crushed waste ceramic was 2.48 g/cm^3, where the value is almost similar to that of natural normal fine aggregate. This statement is further strengthened by Shigeta et al. [48], who reported that the SSD density of waste ceramic coarse aggregate is 2.26 g/cm^3 while natural normal coarse aggregate is 2.62 g/cm^3. Thus, it provides a good effect on the strength of concrete containing crushed waste ceramic material compared to that of plain concrete. Moreover, water absorption of waste ceramic coarse aggregate was 9% compared to natural normal aggregate which recorded 0.67% water absorption. While Suzuki et al. [99] revealed that water absorption of waste ceramic coarse aggregate was 9%, and the crushing rate value was 21.4%, almost similar to that reported by Sato et al. [100]. Thus, the capability of water absorption in ceramic waste aggregates will help in the hydration process of the concrete.

3.4. Superabsorbent Polymer (SAP)

SAP was initially developed during the 1980s and has since been widely used in forestry, agriculture, health supplies, and in other fields given their potential as a water reservoir and their ability to expand and retain water [106–111]. The capability of SAP has been used with cementitious materials in concrete to mitigate shrinkage (autogenous and drying) via self-curing [107,112–116] to enhance the durability toward freeze and thaw deterioration [110,117,118]. Superabsorbent polymers (SAP) are recognized as hydrogels, consisting of a three-dimensional cross-link network structure that can absorb a large volume of liquid compared to their mass because of osmotic pressure and expand to form an insoluble gel [107,118–120]. A chemical reaction will eventuate when SAP is exposed to an aqueous solution, leading to shrinkage or swelling of the SAP. The absorption of SAP is driven by osmotic pressure, as illustrated in Figure 6, before it develops the space between cross-links and polymer chains. The presence of osmotic pressure originates from a concentration gradient of moveable ions between the gel and solution [110,118,121,122]. The swollen SAPs then react as water reservoirs in the concrete. However, as the humidity in the concrete decreases, the absorbed water is pulled back into the cement paste capillary pores. This leads to the SAPs gradually releasing the absorbed water and leaving the voids [118,123].

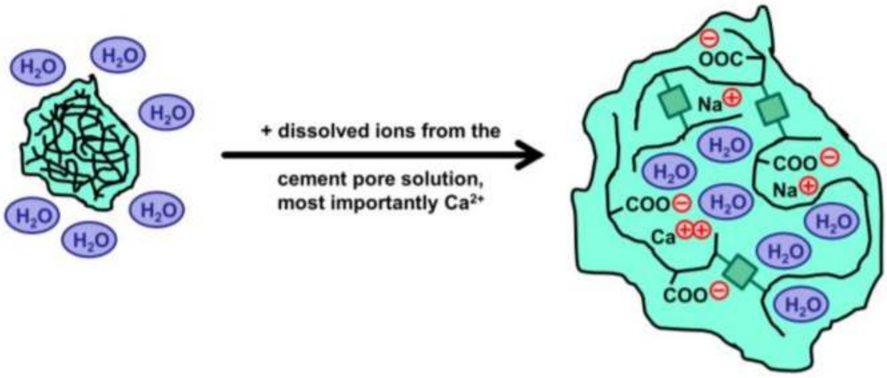

Figure 6. Process of water uptake to SAP [110].

3.5. Polyethylene Glycol (PEG)

Polyethylene-glycol is a condensing polymer of ethylene oxide and water with general formula H (OCH_2CH_2) nOH, where n is the average number of repeated groups of ox ethylene usually between 4 and about 180 [26]. According to Raoult's Law, when the vapor pressure of the solute in the pure condition is less than the vapor pressure of the solvent in the pure condition, it is apparent that theoretically, by adding additives, the vapor pressure of water will decrease, thus reducing the evaporation rate above the concrete surface [26,27,34,55,56]. Therefore, the application of water-soluble polymers for instant PEG as self-curing in concrete has been observed to be both effective and efficient in retaining water and enhancing the hydration process [34,124,125]. Moreover, with water molecules, polymeric chains created by hydrophilic units form hydrogen bonds. A hydrogen bond is a frail bond formed in a compound between hydrogen atoms and strongly electronegative atoms in other molecules [26,126]. The existence of a positive charge at the hydrogen atom causes attraction to the electronegative atom electrostatically as illustrated in Figure 7. To this end, water soluble polymers with either hydroxyl (-OH-) or ether (-O-) functional groups have been used as the chemical to minimize the impact of self-desiccation in concrete [26,126]. Previous researchers have also investigated water retention, hydration, compressive strength, microstructure characteristic, and durability of concrete using PEG as a curing agent [55,56,77,125,127].

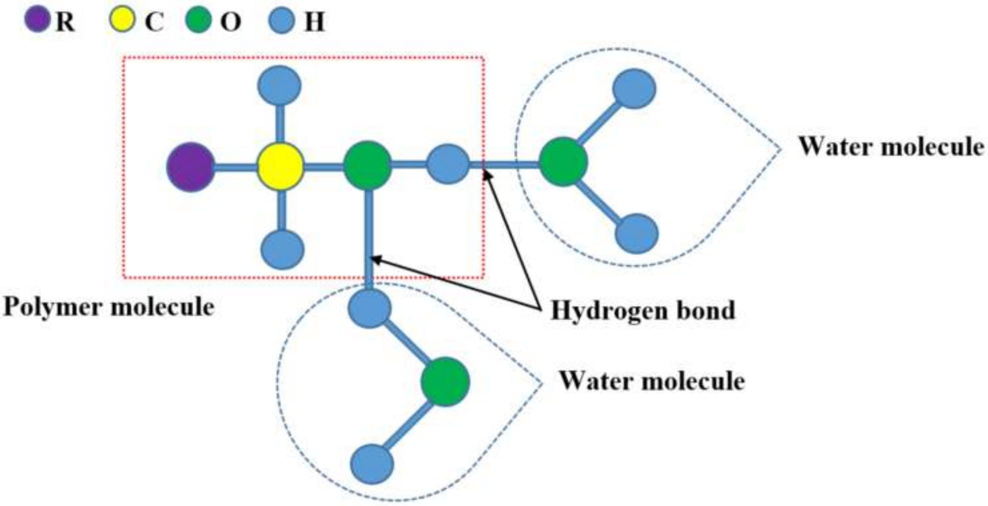

Figure 7. Hydrogen bonds between water molecules and an –OH group on a polymer molecule.

3.6. Natural Fibers (NF)

Previous researchers investigated that wood-derived fibers and powder have potential as self-curing agents in cement-based material due to the former's capability to absorb and retain water in addition to gradually releasing absorbed water [33,57,58,128–131]. Good examples of wood-derived fibers used as self-curing agents in concrete are eucalyptus pulp [33], kenaf fibers [58], and cellulose fibers [57]. Wood-derived fibers are hygroscopic materials, and the movement of water via the pulps depends on the concentration gradient (diffusion) by capillary draw and the effect of osmotic pressure [33,131,132]. Moavenzadeh [133], Elsaid et al. [130] and Jongvisuttisun et al. [33] explained that wood-derived fibers consist of two pores, namely larger pores (e.g., lumen) comprised of free water and smaller pores, as illustrated in Figure 8. Both pores play a key role in the transportation of moisture, from the wood pulp to nearby hydrating cement. Furthermore, the pore solution in cement-based material is alkaline, which therefore influences the character of wood pulp to swell or shrink and to change the effective size of the porous space [134–136], thus affecting the water transport.

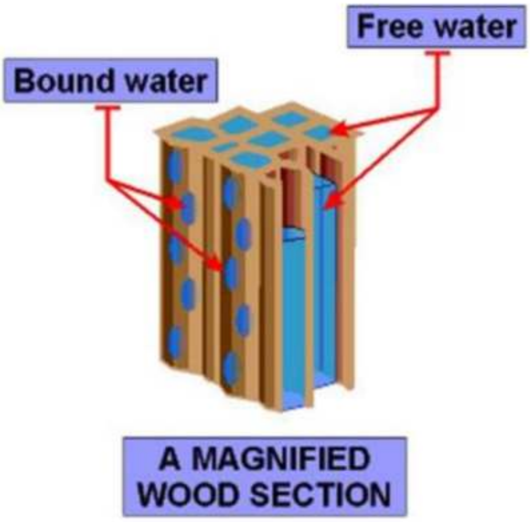

Figure 8. Free and bound water in wood [137].

4. Effects of Self-Curing Agents on Properties of Concrete or Mortar

4.1. Workability

The impact of porous aggregate on the workability of concrete is rarely discussed. The explanation might be that soaked-porous aggregate neither absorbs nor releases water before setting. Hence its workability is unaffected. However, if the dry porous aggregate is added to the mixed concrete, the absorption rate will be slower, resulting in bleeding and segregation of the mixture at the first stage [138]. Thus, a few minutes of pre-mixing of porous aggregate and water is also suggested [139]. In addition, spherical aggregates have been found to improve the workability of fresh concrete [140–143] due to having smaller intrinsic viscosity than other shapes.

Studies have also shown that the addition of SAP caused workability reduction and delays the setting time of concrete [111,144]. Nevertheless, the prewetted SAP resulted in an increasing slump when SAP volume increased. It shows that the spherical particles that pre-absorbed SAP might act as lubricant in concrete mixture, reducing friction between paste and aggregate [111].

4.2. Compressive Strength

Several researchers discovered that porous aggregate decreases the strength of high-performance concrete and the strength stays decreased when the replacement of prewetted porous aggregate is increased [76,145,146]. Other researchers revealed that the reduction in concrete strength is due to the low strength of porous aggregate itself [41,138,147,148]. The detrimental impact of porous aggregate on concrete strength can be mitigated by reducing the size of porous aggregate and improving its distribution [43,93,149]. Generally, the results of compressive strength of concrete at earlier and later ages increased if the optimum proportion was obtained, usually about 20% to 40% replacement of conventional aggregate [104]. However, several researchers revealed that the compressive strength of concrete decreased if the replacement of porous aggregate was more than 50% [38,69,104,150], as shown in Figure 9. The additional water supplied by the prewetted porous aggregate promotes a higher degree of hydration. It fills the pores with hydrated products (C-S-H gel), resulting in an improvement in compressive strength in concrete [63,151]. Agostini et al. [152] discovered that porous aggregate reduced the amount of CH while increasing the density of C-S-H at the interface between the aggregate and the cement paste.

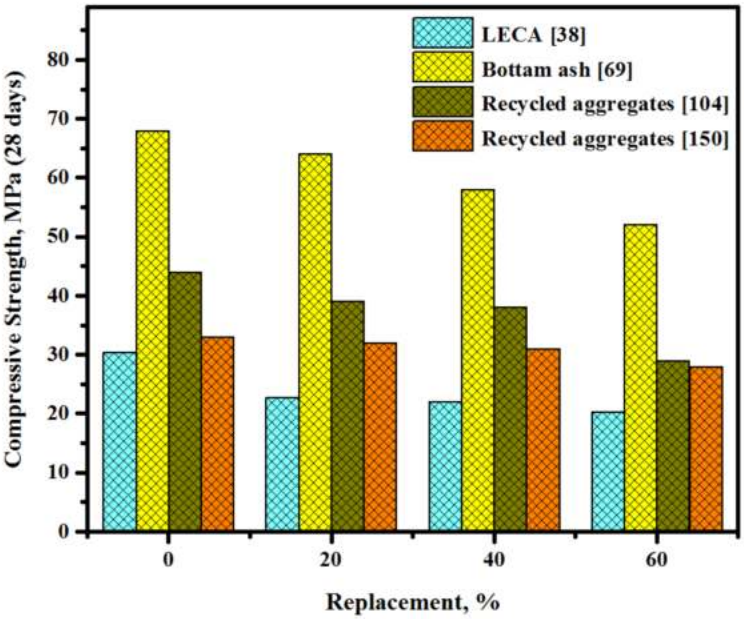

Figure 9. Compressive strength of porous aggregate with percent replacement of conventional aggregate at 28 days.

Many researchers reported SAP improving the compressive strength [32,36,42,80,107,153] of high-performance concrete. However, some of the compressive strength decreased as greater amounts of SAP were added to the concrete [53,154–158], as shown in Table 1. Song et al. [154] studied the effect of SAP on the compressive strength of concrete and indicate that the decreasing of strength due to SAP augments in the concrete. SAP swelled after absorbing water, becoming hydrogels and acting as voids in the cementitious materials [159], as depicted in Figure 10. The results also revealed that the ratio of early-age strength reduction due to SAP addition was more pronounced in the concrete specimen than in the concrete specimen without SAP. Nevertheless, the ratio of the later-age strength depended on the SAP dosage used in the specimen (Table 1). Strength development was increased due to the self-curing by SAP, which resulted in enhanced hydration in the specimens. These results are comparable to observations in other studies [160,161].

Table 1. Compressive strength of mixtures with SAP at 28 days.

Researchers	w/c	Compressive Strength, MPa				
		Reference Concrete	Cement-Based with SAP Addition (% by Weight of Binder)			
[158]			0.1	0.2	0.3	0.8
	0.3	49	52	44	39	34
[155]			0.05	0.16	0.26	-
	0.33	64	62.5	59.4	57.3	-
[53]			0.05	0.09	0.14	-
	0.3	67	73	72	61	-
[156]			0.2	0.4	0.6	-
	0.3	120	114	105	100	-
[157]			0.57	0.86	1.14	-
	0.3	66.71	62.26	58.16	49.28	-
[144]			0.3	0.6	-	-
	0.3	107	99	93	-	-
[154]			0.15	0.3	-	-
	0.4	45	35	25	-	-

The inclusion of water-soluble polymer self-curing agent, polyethylene glycol (PEG) has significantly resulted in an increase of compressive strength in cementitious material compared to specimen without PEG, as reported by previous researchers [162–164]. Mousa et al. [163] studied mixes with and without PEG, prepared and cured in laboratory air at 25 °C. They founded that the samples containing 2% of self-curing agent show 32.5% compressive strength increase at age of 28 days compared to the samples without self-curing agent. The pronounced effect on the compressive strength might be due to normal concrete mixes that were air cured. Vaisakh et al. [164] found that compressive strength air cured mixes with a PEG increase of 5.41% compared to water cured normal mixes. These reports are similar to the study by Rizzuto et al. [162].

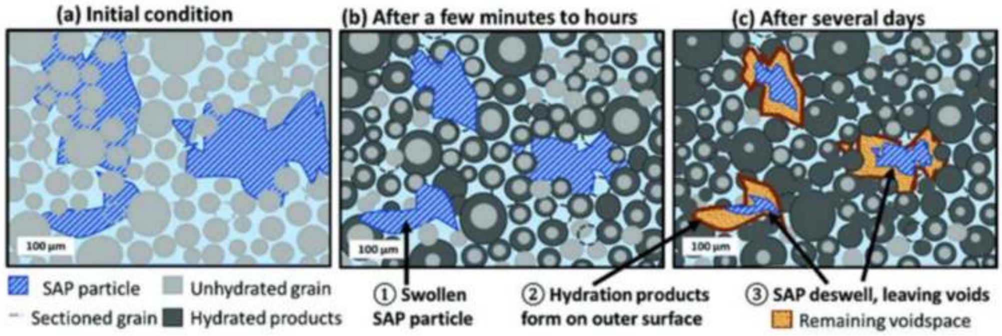

Figure 10. (**a**) Soaked SAPs in the cement mixture; (**b**) SAPs gradually release the absorbed water; (**c**) SAPs de-swell and leave voids [165].

4.3. Autogenous Shrinkage and Drying Shrinkage

Prewetted porous aggregate can more effectively minimize autogenous shrinkage compared to the oven-dry porous aggregate [80,166–169]. This is because of the dry porous aggregate's inability to absorb sufficient additional water from concrete during the plastic stage [139]. Dry porous aggregate can achieve almost the same result as prewetted porous aggregate if it can absorb the required amount of extra water from the concrete mixture [170].

Prewetted porous aggregate gradually released internal curing water, extending the time that internal RH remains at 100%. As a result, this reduces autogenous shrinkage whereby refining pore structure and improving the hydration [138]. Besides, the kinds of LWA might have an impact on their efficacy. Zhuang et al. [171] discovered that prewetted porous aggregate with higher water absorption and lower strength reduces autogenous shrinkage. However, porous aggregate with higher strength and lower water absorption will have a better effect if put in the dry condition. In general, porous aggregate minimizes the total shrinkage at 28 days [172], while nevertheless increasing drying shrinkage [146]. According to Costa et al. [146], a 34% increase in drying shrinkage was observed in the specimen consisting of fine pumice aggregate compared to the reference specimen with conventional aggregates. The increase in drying shrinkage is related to lower elastic modulus and increased water binder ratio [173,174].

The development rate in autogenous shrinkage of high-performance concrete can be minimized by adding SAP (Table 2). Thus, the emergence of cracking can be delayed [175]. The dosage [153,175,176], type [52,56,107,153], particle size [153,175,176], and water-saturated state of SAP [177] play an important role in the efficiency of self-curing. Shen et al. [155] reported that the autogenous shrinkage of self-cured concrete decreased with increase of internal curing water provided by SAP. The rate of autogenous shrinkage reduced as the concrete ages increased, while the autogenous shrinkage rates of all mixtures were remarkably similar at 28 days. The effect of self-curing with varied dosages of SAP on autogenous shrinkage can be related to the extra water supplied by SAP [113]. The water inside the SAP acts as the water contained inside pores at the time of batching, and it is available to assist internal curing while not affecting the initial w/c [178,179]. Internal relative humidity decreases as a result of water loss by self-desiccation during the hydration process, resulting in driving force [107]. Thus, internal curing water is released from SAP into the cement paste, contributing to continuing hydration of cement. A higher dosage of SAP depicts more water being released when autogenous shrinkage is reduced. The drying shrinkage also reduced with the increase of dosage of SAP as reported by Jensen and Hansen [153], Ma et al. [138], Assmann and Reinhardt [180], and Kong et al. [181]. However, if the environment is arid, the water from the SAP particles evaporates quickly, resulting in cracking. The additional water absorbed by the self-curing agent has a considerable impact on the drying shrinkage of self-cured cement-based material.

Using a chemical curing agent such as PEG was also reported to reduce early age shrinkage cracks [182–184]. Amin et al. [183] investigated engineering properties on self-curing concrete by using polyethylene glycol. The results revealed that adding PEG to the concrete mixes to perform the self-curing role contributes to reducing dry shrinkage compared with reference concrete. Hence, the application of the self-curing explained in this research increased the subsequent degree of hydration of cement and the chemical shrinkage, consequently effectively reducing early and late shrinkage. However, only a few researchers had investigated the autogenous and drying shrinkage of concrete when PEG was used as a curing agent.

4.4. Effect of Curing Agent on Interfacial Transition Zone

The interfacial transition zone (ITZ) between cement pastes and aggregate is the most important interface in concrete. There is high porosity and more calcium hydroxide ($Ca(OH)_2$) and ettringite in ITZ between cement paste and conventional aggregate [141]. However, a thin and denser ITZ was formed between porous aggregate and cement paste matrix [168,185–187], as depicted in Figure 11.

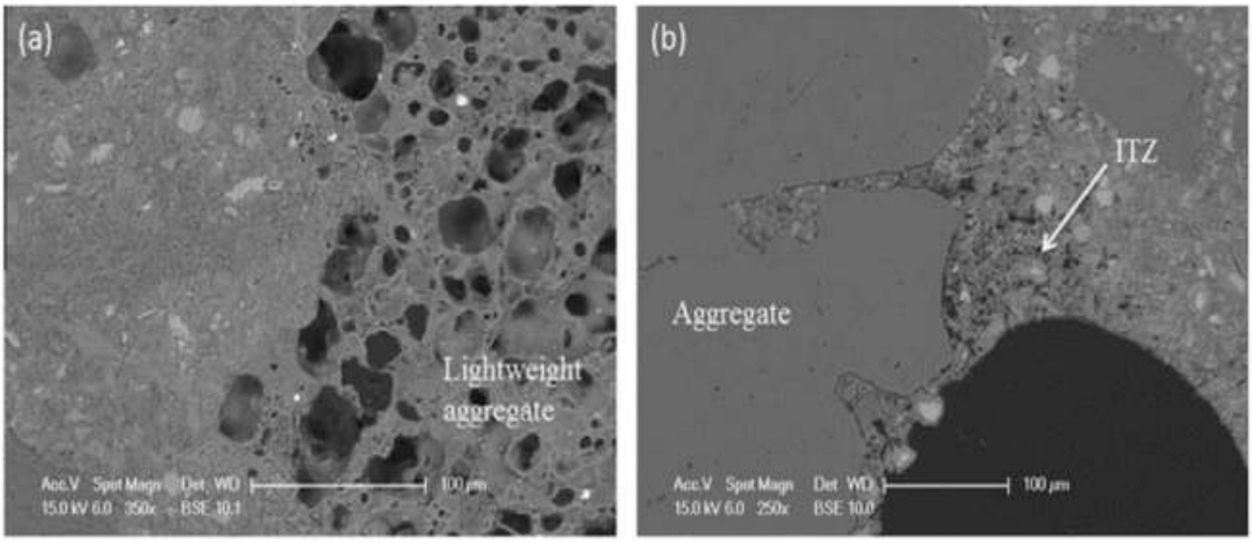

Figure 11. ITZ microstructure in cement mortar (**a**) with porous aggregate, (**b**) with conventional aggregate [187].

The formation of C-S-H in high quantities [42,99,104,152] and the homogeneousness [188,189] are also improved in ITZ. Thus, it enhances the strength of internally curing concrete and establishes a well bonding [104] between porous aggregate and cement paste at ITZ. Moreover, some hydrated products that were discovered in pores of porous aggregate contributed to an increase in strength at later ages [42,190,191]. Sun et al. [187] applied SEM techniques to compute the ITZ microstructure, founded a 3D digital model of ITZ using 3D image reconstruction techniques, and applied the mesoscale chemo thermal-hydraulic model to simulate the development of ITZ. The research revealed that internal curing can improve the durability of concrete. It is proposed that multi-physical hydration models be linked to microstructure characterization and transport properties in order to examine ITZ microstructure development.

The additional of SAP could also enhance the degree of hydration and densify the cement matrix on the surrounding SAP [192,193]. However, the water release from SAP can leaves pores [110,194] and undermine the properties of the cement matrix [181]. Studies revealed by Jianhui [195] reported that the development of pores can impair the ITZ and bond strength between SAP and the cement matrix as shown in Figure 12. This effect increased as the SAP content and particle size of the SAP increased. Ridi et al. [196] found that the incorporation of SAP into high-performance concrete (HPC) helps the densification of the microstructure of the concrete. They also discovered via experimentation that the self-curing procedure is associated with increased strength, a higher degree of hydration, and penetration resistance in heat-cured concrete, as well as a better microstructure with a lower porosity in HPC.

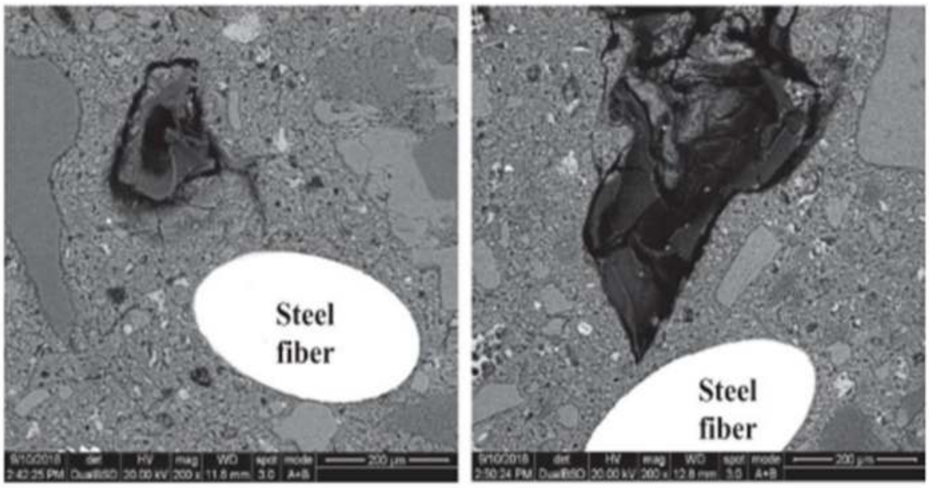

Figure 12. The microstructure of the high-performance concrete with SAP [195].

5. Environmental Benefits of Self-Curing Concrete or Mortar

The utilization of natural aggregates has become a growing issue, given the excessive use for construction purposes. In addition, to reduce wastage and recycling, by-products have attracted growing interest and attention from researchers. As such, the development of new methods in managing waste has swiftly become one of the most important research topics. The increasing need to reuse materials, given diminishing natural resources, has become a recognized and volatile issue healthy debated by scholars and researchers. Accordingly, research studies have increasingly investigated artificial aggregates for infrastructure construction as a replacement for natural aggregates. Most artificial aggregates produced from waste or by-products, [42,197–199] and their unique properties, such as porosity and absorption capacity, have the added benefits of supplying water internally for self-curing concrete [48,84,163]. In addition, using large quantities of industrial and agricultural waste can help to reduce suspension in natural aggregates [200,201]. Moreover, it is seen as an effective process to convert waste or by-products into valuable building materials. Thus, this leads to beneficial performance for the economy whereby it produces cheaper mortar and concrete materials for low-cost construction [42]. The utilization of artificial aggregates produced from waste materials will also aid in the reduction and usage of materials made from chemical resources as curing agents in concrete. Furthermore, it positively contributes to safeguarding and protecting the environment leading to sustainable development and reduces carbon emission [200]. Besides, waste material as a curing agent replacing natural aggregates in concrete will lead to the reduction in landfills and prevent natural resources such as flora and fauna from being destroyed [199].

The review of research on self-curing concrete revealed it to be both dense and durable compared to conventional non-cured concrete, [124,138,202] thus increasing the building's lifespan (i.e., service life). Therefore, demolition activities and maintenance work on such structures can reduce concrete rubble as waste construction material. The growing scarcity of water resources in hot climates, such as in Afro-Asian regions, has also required regular checking on the use of freshwater for concrete production, given the approximate rate of 3 m^3 for every 1 m^3 of concrete produced for curing purposes [28,56]. Therefore, the techniques for self-curing concrete need to be monitored and advanced, where possible, by conserving the use of freshwater. For example, unneeded water spraying or water sprinkling techniques are needless and should be avoided. Therefore, the self-curing curing agent provides an avenue for further cement hydration via the absorption of water before or during the mixing of concrete as the absorbed water can be slowly released during the process of hardened concrete [32,138].

Table 2. Effect of self-curing agents and curing condition on concrete workability, engineering, and microstructure performance.

Curing Agent	Concrete Type	Curing Agent Replacement	Curing Condition	Finding	Ref.
Lightweight aggregate Leca/Expanded shale	Normal-strength concrete	Leca 12.5–50% Shale 10–30%	Saturated-surface dry (SSD)/water	Workability: The use of lightweight aggregates did not alter the predesigned slump of the mix due to the incorporation of the aggregate in a pre-soaked saturated surface dry condition. Strength at 28 days: For Leca: Reduced by 22% to 29%. For Shale: Reduced by 8% to 18%. The lowered compressive strength did not violate the minimum strength required for highway construction projects of 3000 psi. Reduction ratio of autogenous shrinkage at 28 days (%): For Leca: Reduced by 7.5% to 25%. For Shale: Reduced by 10% to 25%.	[38]
Lightweight aggregate Leca/Fly ash	High-performance concrete	For both 5–25%	Saturated-surface dry (SSD) air	Workability: Increased by 0.5 to 1% for both Leca and Fly ash. Slump flow of all the mixes with Leca and fly ash varied from 680 to 710 mm which is within the desired range of 650 to 800 mm.	[203]
Lightweight aggregate Volcanic tuff	High-performance concrete	5–20%	Saturated-surface dry (SSD)/water	Workability: Slump values reduced with an increase in the LWA content. Even LWA prepared in SSD condition, assuming that LWAs could have lost some amount of internal water giving the pores free space to absorb additional water from the mixture. Strength at 28 days: Reduced by 2.3% to 18.6%. Reduction ratio of autogenous shrinkage at 28 days (%): 33% to 54%.	[204]

Table 2. *Cont.*

Curing Agent	Concrete Type	Curing Agent Replacement	Curing Condition	Finding	Ref.
Lightweight aggregate Autoclaved Aerated Concrete aggregate (AAC)	High-performance concrete	20–60%	Saturated-surface dry (SSD)/water/air	Slump: The slump value was increased due to water retain ability, extra water on the surface of AAC particles. Compared to control sample (580 mm), the slump value increased to 890, 950, and 1060 mm with increasing LWAs to 20%, 40%, and 60%, respectively. Strength at 28 days: Water curing: Reduced by 11.4% to 36%. Air curing: For 20 and 40% achieved increment by 0.2 to 5.4%. However, the increasing level of LWAs to 60% led to drop the strength by 25%. Microstructure: Reserved water in AAC aggregates would, be transferred to cement paste across ITZ, increasing hydration level to the cement binders. The strength improvement in later age was mainly influenced by more C-S-H formation and denser microstructures. The usage of AAC-LWA in SSD condition would provide higher strength in all cases than the as- received/dry AAC-LWA.	[104]
Lightweight aggregate Leca	High-performance concrete	10–25%	Saturated-surface dry (SSD)/water curing, followed by air curing	Strength at 28 days: With increasing LWAs content, the gain in strength dropped from 15% to 2%.	[205]
Lightweight aggregate Leca/PEG	Normal-strength concrete	Leca 10–20% PEG 1–3%	Saturated-surface dry (SSD)/air	Strength at 28 days: For Leca: Increased by 5 to 13.3%. For PEG: Increased by 13.3 to 15%. Compressive strength systematically increases as leca increased. This may be attributed to the continuation of the hydration process by store water in the SSD Leca resulting in lower voids and pores and greater bond force between the cement paste and aggregate.	[79]
Polymer/PEG	Normal-strength concrete	Polymer (SAP) 0.35–1% PEG 0.25–2%	Air	Strength at 28 days: For polymer: The gain on strength trend to increase with increasing SAP content and reduction in water/cement ratio from 0.60 to 0.40%. For PEG: Similar trend of results was observed and the gain in strength trend to increase with increasing PEG content and reduce the water/cement ratio.	[56]

Table 2. *Cont.*

Curing Agent	Concrete Type	Curing Agent Replacement	Curing Condition	Finding	Ref.
Polymer	High-performance concrete	0.2–0.6%	Saturated-surface dry (SSD)	Strength: Reduced by 3.3% to 10%. The strength loss was more accentuated when higher contents of SAP were used regardless of size and type of SAP. The negative effect of SAP on strength development of UHPC was related to the formation of voids after the release of the absorbed water from SAP to the matrix. Shrinkage: Reduced by 33% to 66.7%. The increase in the content of SAP, regardless of size, reduced the autogenous shrinkage significantly.	[156]
Polymer	High-performance concrete	0.3%	Air-dry (AD)	Workability: Enhance the workability performance. Strength: Reduced the compressive strength by 8.5%. It may be concluded that the shape and size of the SAP particles may have a major influence on the strength values. Shrinkage: Reduced by 50%. Polymer mitigates the autogenous shrinkage ofconcrete very effectively	[110]
Polymer	High-performance concrete	0.17–0.49%	Saturated-surface dry (SSD)/air	The HPC internally cured with SAPs showed a lower autogenous shrinkage than that without SAPs, which was due to the decreased self-desiccation of HPC internally cured with SAPs.	[157]
PEG/Polymer	High-performance concrete	PEG 0.5–2.0% SAP 0.25–1.0%	Saturated-surface dry (SSD)	Strength at 28 days: For PEG: Reduced by 0.4 to 8%. For polymer: Reduced by 7.6 to 24.6%.	[34]
PEG	Normal strength concrete/High-performance concrete	0.1–1.0%	Water/Air/Sealed	Workability: Improved with inclusion of PEG. With increase in dosage of PEG, the flowability of concrete has improved. This is due to low viscous nature.Strength at 28 days: Enhanced by 14.3 to 25%. Microstructure: Use of PEG chemicals resulted in a dense microstructure with a calcium/silica of 1.12. This is an indication of stable C-S-H gel formation compared to non-cured specimens. While non-cured specimens exhibited poor microstructure with interlinking of micro cracks and ettringite formation. Test involved XRD and SEM.	[55]

Table 2. *Cont.*

Curing Agent	Concrete Type	Curing Agent Replacement	Curing Condition	Finding	Ref.
Natural fibres	High-performance concrete	0.8–1%	Saturated-surface dry (SSD)/Air-dry (AD)	Microstructure: Internal curing mechanisms of hardwood eucalyptus pulp-cement composites and then uses SEM, XPS, and AFM to examine interactions between the fiber and surrounding hydrating cement. Addition of eucalyptus pulps as internal curing agents may slightly delay setting. Observations by XPS show development of calcium silicate hydrate and calcium hydroxide at cement paste.	[33]
Natural fibres	High-performance concrete	1.2–2.4%	Air-dry (AD)	Tests included in microstructure test are SEM, Atomic Force Microscopy (AFM), and Nanoindentation test in order to examine the effect of kenaf on the hydration and micromechanics of concrete.	[58]
Polymer/Micritic calcite aggregate (ANWA)	High-performance concrete	100%	Saturated-surface dry (SSD)/Air-dry (AD)/Sealed	Workability: the workability of concrete enhanced with inclusion both polymer and micritic calcite aggregates. The concrete mixture achieved a slight increased slump that was attributed to the instant adhesion of cement particles on the aggregates surface that smoothed out their rough surface. Strength at 28 days: For both curing condition and curing agents, the compressive strength reduced by 0.9 to 19%. Shrinkage at 28 days: Reduced by 42.9 to 96.4%. Concrete mixtures containing self-curing agent exhibited a significant reduction of autogenous shrinkage.	[206]
Porous ceramic aggregate (PCA)	High-performance concrete	10–20%	Saturated-surface dry (SSD)	Strength at 28 days: The compressive strength of concrete with PCA is higher than control concrete. In particular, the compressive strength of 20% is more than 15% higher than control concrete at age 28 days. Microstructures: Consequently, this study shows the possibility that the internal curing water supply improves the micro-hardness of the ITZ around PCA. The improvement of the ITZ leads to an increase in the compressive strength of concrete	[48]

Table 2. *Cont.*

Curing Agent	Concrete Type	Curing Agent Replacement	Curing Condition	Finding	Ref.
Porous ceramic aggregate (PCA)	Normal strength concrete.	10–20%	Saturated-surface dry (SSD)	Workability: Enhancement on slump values were observed. Strength at 28 days: A 10% replacement of coarse aggregate by PCA was more effective in improving compressive strength than a 20% replacement by PCA at the early ages of 3 and 7 days, independent of exposure conditions. Shrinkage at 28 days: Internal curing using PCA to replace part of the coarse aggregate was not effective in reducing autogenous shrinkage, which could be explained by the comparatively high water-to-cement ratio of 0.55 of the present concrete.	[100]

6. Conclusions

After undertaking the literature review in this field, it can be concluded that many researchers have investigated the influence of different materials as curing agents toward physical and mechanical properties, shrinkage (autogenous and drying), and microscopic in self-curing concrete. Evidence supports the fact that all curing agents can be used given their capability to absorb water and act as a water reservoir in concrete, thereby gradually releasing water for the hydration process. The use of curing agents was also shown to have a favorable effect on the properties of self-curing concrete, comparable to conventional concrete.

The effect of self-curing by porous aggregate and SAP depends on the amount, particle size, and pore structure of curing agent in concrete. If the amount, particle size, and pore structure of those curing agents substantially increase, it may cause a substantial decrease in strength in high-performance cement-based materials. Many studies have reported an increase in compressive strength of high-performance concrete when the optimum proportion of replacement of conventional aggregate is obtained. The incorporation of internal curing water would reduce total shrinkage at early and later age by change in internal RH and the saturation degree of capillary pores. As a result, this enhances hydration and refines pore structures in cementitious materials. A self-curing agent promotes the hydration of ITZ and improves the bonding between cement paste matrix and porous aggregate or SAP or PEG, thus increasing the density of ITZ. This improvement reduces porosity and pore connectivity, leads to reduced permeability, and finally enhances the strength and durability of cementitious material.

Based on the work and requirements that have been highlighted in this study, a number of recommendations are purposed for future research: (i) The curing effect is difficult to control since typical curing materials are only capable of absorbing and desorbing the water and the uniform distribution in concrete makes it difficult to have artificial modification. Hence, intelligent materials are introduced, such as humidity sensors embedded in microcapsules; this may improve internal curing conditions. (ii) There are many investigations on the effect of internal curing of high-performance cement-based materials. However, the studies on the effect of normal strength of self-curing cementitious material is very limited. Therefore, the investigation on the physical, mechanical, and microscopic properties of normal strength of self-curing cementitious materials is looked into. (iii) Particle size, amount, and distribution in concrete of porous aggregate and self-curing agent SAP, as well as the amount of internal curing water, only exist in theoretical analysis. There is no suitable or acceptable technique to define the ITZ range between porous aggregate or SAP and cement paste. Still, the specified method is significant for designing the amount, size, and distribution of a porous aggregate or SAP and internal curing water.

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Abbreviations

LWA:	Artificial lightweight aggregate
SAP:	Superabsorbent polymers
PEG:	Polyethylene glycol
ANWA:	Artificial normal-weight aggregate
LECA:	Expanded clay
RH:	Rice husk ash
ITZ:	Interfacial transition zone
C-S-H:	Calcium silicate hydrate
OPC:	Ordinary Portland cement
CH:	Calcium hydroxide
Ca_3SiO_5:	Alite
Ca_2SiO_4:	Belite
$Ca_4Al_2Fe_2O_{10}$:	Ferrite
$Ca_3Al_2(OH)_{12}$:	Hydrogarnet
$Ca_3Al_2O_6$:	Aluminate
$CaSO_4·2H_2O$:	Gypsum
$[Ca_3Al(OH)_6·12H_2O]_2(SO_4)·32H_2O$:	Ettringite
$[Ca_2Al(OH)_6·2H_2O]_2(SO_4)·2H_2O$:	Monosulfate
HPC:	High-performance concrete
SCMs:	Supplementary cementitious material

References

1. Huseien, G.F.; Sam, A.R.M.; Algaifi, H.A.; Alyousef, R. Development of a sustainable concrete incorporated with effective microorganism and fly Ash: Characteristics and modeling studies. *Constr. Build. Mater.* **2021**, *285*, 122899. [CrossRef]
2. James, T.; Malachi, A.; Gadzama, E.W.; Anametemok, A. Effect of Curing Methods on the Compressive Strength of Concrete. *Niger. J. Technol.* **2011**, *30*, 14–20. [CrossRef]
3. Nahata, Y.; Kholia, N.; Tank, T. Effect of Curing Methods on Efficiency of Curing of Cement Mortar. *APCBEE Procedia* **2014**, *9*, 222–229. [CrossRef]
4. Mohamad, D.; Beddu, S.; Sadon, S.N.; Kamal, N.L.M.; Itam, Z.; Zainol, M.A.; Ramli, M.Z.; Sapuan, W.M. Properties of self-curing concrete containing bottom ash. *Int. J. Adv. Appl. Sci.* **2017**, *4*, 138–142. [CrossRef]
5. Parrott, L.-J.; Illston, J.M. Load-Induced Strains in Hardened Cement Paste. *J. Eng. Mech. Div.* **1975**, *101*, 13–24. [CrossRef]
6. Spears, R.E. The 80 percent solution to inadequate curing problems. *Concr. Int.* **1983**, *5*, 15–18.
7. Safiuddin, M.; Raman, S.N.; Zain, M.F.M. Effect of different curing methods on the properties of microsilica concrete. *Aust. J. Basic Appl. Sci.* **2007**, *1*, 87–95.
8. Rajappan, P.; Kishore, G.V.V.S.R.; Sundaramurthy, C.; Pillai, C.S.; Laharia, A.K. Effect of curing methods and environment on properties of concrete. *Concr. Res. Lett.* **2014**, *5*, 786–811. [CrossRef]
9. McCarter, W.J.; Ben-Saleh, A.M. Influence of practical curing methods on evaporation of water from freshly placed concrete in hot climates. *Build. Environ.* **2001**, *36*, 919–924. [CrossRef]
10. Ye, D.; Shon, C.-S.; Mukhopadhyay, A.K.; Zollinger, D.G. New Performance-Based Approach to Ensure Quality Curing during Construction. *J. Mater. Civ. Eng.* **2010**, *22*, 687–695. [CrossRef]
11. ACI Committee 308. *Guide to Curing Concrete*; American Concrete Institute: Farmington Hills, MI, USA, 2001.
12. Bushlaibi, A.H. Effects of environment and curing methods on the compressive strength of silica fume high-strength concrete. *Adv. Cem. Res.* **2004**, *16*, 17–22. [CrossRef]
13. Soler, J.M. *Thermodynamic Description of the Solubility of CSH Gels in Hydrated Portland Cement*; Literature Review; Posiva Oy: Eurajoki, Finland, 2007; pp. 1–36.
14. Akinwumi, I.I.; Gbadamosi, Z.O. Effects of curing condition and curing period on the compressive strength development of plain concrete. *Int. J. Civ. Environ. Res.* **2014**, *1*, 83–99.
15. Samadi, M.; Huseien, G.F.; Mohammadhosseini, H.; Lee, H.S.; Lim, N.H.A.S.; Tahir, M.M.; Alyousef, R. Waste ceramic as low cost and eco-friendly materials in the production of sustainable mortars. *Jour. of Clean. Prod.* **2020**, *266*, 121825. [CrossRef]
16. Yazici, H.; Aydın, S.; Yiğiter, H.; Baradan, B. Effect of steam curing on class C high-volume fly ash concrete mixtures. *Cem. Concr. Res.* **2005**, *35*, 1122–1127. [CrossRef]

17. Gonzalez-Corominas, A.; Etxeberria, M.; Poon, C.S. Influence of steam curing on the pore structures and mechanical properties of fly-ash high performance concrete prepared with recycled aggregates. *Cem. Concr. Compos.* **2016**, *71*, 77–84. [CrossRef]
18. Mei, J.; Ma, B.; Tan, H.; Li, H.; Liu, X.; Jiang, W.; Zhang, T.; Guo, Y. Influence of steam curing and nano silica on hydration and microstructure characteristics of high volume fly ash cement system. *Constr. Build. Mater.* **2018**, *171*, 83–95. [CrossRef]
19. Prommas, R.; Rungsakthaweekul, T. Effect of Microwave Curing Conditions on High Strength Concrete Properties. *Energy Procedia* **2014**, *56*, 26–34. [CrossRef]
20. Rattanadecho, P.; Makul, N.; Pichaicherd, A.; Chanamai, P.; Rungroungdouyboon, B. A novel rapid microwave-thermal process for accelerated curing of concrete: Prototype design, optimal process and experimental investigations. *Constr. Build. Mater.* **2016**, *123*, 768–784. [CrossRef]
21. Mgbemena, C.O.; Li, D.; Lin, M.-F.; Liddel, P.D.; Katnam, K.B.; Thakur, V.K.; Nezhad, H.Y. Accelerated microwave curing of fibre-reinforced thermoset polymer composites for structural applications: A review of scientific challenges. *Compos. Part A Appl. Sci. Manuf.* **2018**, *115*, 88–103. [CrossRef]
22. Huseien, G.F.; Joudah, Z.H.; Memon, R.P.; Sam, A.R.M. Compressive strength and microstructure properties of modified concrete incorporated effective microorganism and fly ash. *Mater. Today Proc.* **2021**, *46*, 2036–2044. [CrossRef]
23. Kovtun, M.; Ziolkowski, M.; Shekhovtsova, J.; Kearsley, E. Direct electric curing of alkali-activated fly ash concretes: A tool for wider utilization of fly ashes. *J. Clean. Prod.* **2016**, *133*, 220–227. [CrossRef]
24. Cecini, D.; Austin, S.A.; Cavalaro, S.; Palmeri, A. Accelerated electric curing of steel-fibre reinforced concrete. *Constr. Build. Mater.* **2018**, *189*, 192–204. [CrossRef]
25. Huseien, G.F.; Joudah, Z.H.; Khalid, N.H.A.; Sam, A.R.M.; Tahir, M.M.; Lim, N.H.A.S.; Alyousef, R.; Mirza, J. Durability performance of modified concrete incorporating fly ash and effective microorganism. *Constr. Build. Mater.* **2021**, *267*, 120947. [CrossRef]
26. Dhir, R.K.; Hewlett, P.C.; Lota, J.S.; Dyer, T.D. An investigation into the feasibility of formulating 'self-cure' concrete. *Mater. Struct.* **1994**, *27*, 606–615. [CrossRef]
27. Dhir, R.K.; Hewlett, P.C.; Dyer, T.D. Mechanisms of water retention in cement pastes containing a self-curing agent. *Mag. Concr. Res.* **1998**, *50*, 85–90. [CrossRef]
28. Sampebulu, V. Increase on strengths of hot weather concrete by self-curing of wet porous aggregate. *Civil Eng. Dimens.* **2012**, *14*, 92–99.
29. Namsone, E.; Šahmenko, G.; Korjakins, A.; Namsone, E. Influence of porous aggregate on the properties of foamed concrete. *Constr. Sci.* **2016**, *19*, 13–20. [CrossRef]
30. Bentz, D.P.; Lura, P.; Roberts, J.W. Mixture proportioning for internal curing. *Concr. Int.* **2005**, *27*, 35–40.
31. Sant, G.; Bentz, D.; Weiss, J. Capillary porosity depercolation in cement-based materials: Measurement techniques and factors which influence their interpretation. *Cem. Concr. Res.* **2011**, *41*, 854–864. [CrossRef]
32. Liu, J.; Shi, C.; Ma, X.; Khayat, K.; Zhang, J.; Wang, D. An overview on the effect of internal curing on shrinkage of high performance cement-based materials. *Constr. Build. Mater.* **2017**, *146*, 702–712. [CrossRef]
33. Jongvisuttisun, P.; Leisen, J.; Kurtis, K.E. Key mechanisms controlling internal curing performance of natural fibers. *Cem. Concr. Res.* **2018**, *107*, 206–220. [CrossRef]
34. Sastry, K.V.S.G.K.; Kumar, P.M. Self-curing concrete with different self-curing agents. *IOP Conf. Ser. Mater. Sci. Eng.* **2018**, *330*, 012120. [CrossRef]
35. Memon, R.P.; Sam, A.R.M.; Awang, A.Z.; Memon, U.I. Effect of Improper Curing on the Properties of Normal Strength Concrete. *Eng. Technol. Appl. Sci. Res.* **2018**, *8*, 3536–3540. [CrossRef]
36. Memon, R.P.; Sam, A.R.M.; Awang, A.Z.; Tahir, M.M.; Mohamed, A.; Kassim, K.A.; Ismail, A. Introducing Effective Microorganism as Self-curing Agent in Self-cured Concrete. *InIOP Conf. Ser. Mater. Sci. Eng.* **2020**, *849*, 012081. [CrossRef]
37. Meeks, K.W.; Carino, N.J. *Curing of High-Performance Concrete: Report of the State-of-the-Art*; Building and Fire Research Laboratory, National Institute of Standards and Technology: Gaithersburg, MD, USA, 1999; pp. 1–203.
38. Akhnoukh, A.K. Internal curing of concrete using lightweight aggregates. *Part. Sci. Technol.* **2017**, *36*, 362–367. [CrossRef]
39. Kevern, J.T.; Nowasell, Q.C. Internal curing of pervious concrete using lightweight aggregates. *Constr. Build. Mater.* **2018**, *161*, 229–235. [CrossRef]
40. Kim, H.-K. Internal Curing and Improved Chloride Resistance of High-Strength Concrete Amended with Coal Bottom. Ph.D. Thesis, Korea Advanced Institute of Science and Technology, Daejeon, Korea, 2013.
41. Zhutovsky, S.; Kovler, K. Influence of water to cement ratio on the efficiency of internal curing of high-performance concrete. *Constr. Build. Mater.* **2017**, *144*, 311–316. [CrossRef]
42. Al Saffar, D.M.; Al Saad, A.J.; Tayeh, B.A. Effect of internal curing on behavior of high performance concrete: An overview. *Case Stud. Constr. Mater.* **2019**, *10*, e00229. [CrossRef]
43. Liu, F.; Wang, J.; Qian, X.; Hollingsworth, J. Internal curing of high performance concrete using cenospheres. *Cem. Concr. Res.* **2017**, *95*, 39–46. [CrossRef]
44. Van, V.-T.A.; Rößler, C.; Bui, D.-D.; Ludwig, H.-M. Rice husk ash as both pozzolanic admixture and internal curing agent in ultra-high performance concrete. *Cem. Concr. Compos.* **2014**, *53*, 270–278. [CrossRef]

45. Ye, G.; van Tuan, N.; Hao, H. Rice husk ash (RHA) as smart materials to mitigate autogenous shrinkage in high (ultra-high) performance concrete. In Proceedings of the 3rd International Conference on Sustainable Construction Materials and Technologies (SCMT2013), Kyoto, Japan, 18–22 August 2013.
46. Abate, S.Y.; Song, K.-I.; Song, J.-K.; Lee, B.Y.; Kim, H.-K. Internal curing effect of raw and carbonated recycled aggregate on the properties of high-strength slag-cement mortar. *Constr. Build. Mater.* **2018**, *165*, 64–71. [CrossRef]
47. Lee, N.K.; Abate, S.Y.; Kim, H.-K. Use of recycled aggregates as internal curing agent for alkali-activated slag system. *Constr. Build. Mater.* **2018**, *159*, 286–296. [CrossRef]
48. Shigeta, A.; Ogawa, Y.; Kawai, K. Microscopic investigation on concrete cured internally by using porous ceramic roof-tile waste aggregate. *MATEC Web Conf.* **2018**, *195*, 01004. [CrossRef]
49. Riyazi, S.; Kevern, J.; Mulheron, M. Super absorbent polymers (SAPs) as physical air entrainment in cement mortars. *Constr. Build. Mater.* **2017**, *147*, 669–676. [CrossRef]
50. Almeida, F.C.R.; Klemm, A.J. Efficiency of internal curing by superabsorbent polymers (SAP) in PC-GGBS mortars. *Cem. Concr. Compos.* **2018**, *88*, 41–51. [CrossRef]
51. Kang, S.-H.; Hong, S.-G.; Moon, J. Importance of drying to control internal curing effects on field casting ultra-high performance concrete. *Cem. Concr. Res.* **2018**, *108*, 20–30. [CrossRef]
52. Oh, S.; Choi, Y.C. Superabsorbent polymers as internal curing agents in alkali activated slag mortars. *Constr. Build. Mater.* **2018**, *159*, 1–8. [CrossRef]
53. Woyciechowski, P.P.; Kalinowski, M. The Influence of Dosing Method and Material Characteristics of Superabsorbent Polymers (SAP) on the Effectiveness of the Concrete Internal Curing. *Materials* **2018**, *11*, 1600. [CrossRef]
54. Bashandy, A. Self-Curing Concrete under Sulfate Attack. *Arch. Civ. Eng.* **2016**, *62*, 3–18. [CrossRef]
55. Chand, M.S.R.; Giri, P.S.N.R.; Pancharathi, R.K.; Kumar, G.R.; Raveena, C. Effect of self curing chemicals in self compacting mortars. *Constr. Build. Mater.* **2016**, *107*, 356–364. [CrossRef]
56. Sarbapalli, D.; Dhabalia, Y.; Sarkar, K.; Bhattacharjee, B. Application of SAP and PEG as curing agents for ordinary cement-based systems: Impact on the early age properties of paste and mortar with water-to-cement ratio of 0.4 and above. *Eur. J. Environ. Civ. Eng.* **2016**, *21*, 1237–1252. [CrossRef]
57. Kawashima, S.; Shah, S.P. Early-age autogenous and drying shrinkage behavior of cellulose fiber-reinforced cementitious materials. *Cem. Concr. Compos.* **2011**, *33*, 201–208. [CrossRef]
58. Zadeh, V.Z.; Bobko, C.P. Nano-mechanical properties of internally cured kenaf fiber reinforced concrete using nanoindentation. *Cem. Concr. Compos.* **2014**, *52*, 9–17. [CrossRef]
59. Bentz, D.P.; Weiss, W.J. *Internal Curing: A 2010 State-of-the-Art Review*; US Department of Commerce, National Institute of Standards and Technology: Gaithersburg, MD, USA, 2011; pp. 1–82.
60. Grasley, Z.C.; Lange, D.; D'Ambrosia, M.D. Internal relative humidity and drying stress gradients in concrete. *Mater. Struct.* **2006**, *39*, 901–909. [CrossRef]
61. Zhang, J.; Huang, Y.; Qi, K.; Gao, Y. Interior Relative Humidity of Normal- and High-Strength Concrete at Early Age. *J. Mater. Civ. Eng.* **2012**, *24*, 615–622. [CrossRef]
62. Yadav, N.; Deo, D.S.V.; Ramtekkar, D.G. Mechanism and benefits of internal curing of concrete using light weight aggregates and its future prospects in indian construction. *Int. J. Civ. Eng. Technol.* **2017**, *8*, 323–334.
63. Weber, S.; Reinhardt, H.W. A New Generation of High Performance Concrete: Concrete with Autogenous Curing. *Adv. Cem. Based Mater.* **1997**, *6*, 59–68. [CrossRef]
64. Nguyen, H.D.; Le, H.Q. Water movement in Internally Cured Concrete. *IOP Conf. Ser. Mater. Sci. Eng.* **2018**, *365*, 032029. [CrossRef]
65. Paul, Á.; Lopez, M. Assessing Lightweight Aggregate Efficiency for Maximizing Internal Curing Performance. *ACI Mater. J.* **2011**, *108*, 385–393. [CrossRef]
66. de Sensale, G.R.; Goncalves, A.F. Effects of Fine LWA and SAP as Internal Water Curing Agents. *Int. J. Concr. Struct. Mater.* **2014**, *8*, 229–238. [CrossRef]
67. Zhutovsky, S.; Kovler, K.; Bentur, A. Efficiency of lightweight aggregates for internal curing of high strength concrete to eliminate autogenous shrinkage. *Mater. Struct.* **2002**, *35*, 97–101. [CrossRef]
68. Akcay, B.; Tasdemir, M.A. Effects of distribution of lightweight aggregates on internal curing of concrete. *Cem. Concr. Compos.* **2010**, *32*, 611–616. [CrossRef]
69. Kim, H.-K.; Ha, K.; Lee, H. Internal-curing efficiency of cold-bonded coal bottom ash aggregate for high-strength mortar. *Constr. Build. Mater.* **2016**, *126*, 1–8. [CrossRef]
70. Zhang, B.; Poon, C.S. Internal curing effect of high volume furnace bottom ash (FBA) incorporation on lightweight aggregate concrete. *J. Sustain. Cem. Mater.* **2017**, *6*, 366–383. [CrossRef]
71. Zou, D.; Li, K.; Li, W.; Li, H.; Cao, T. Effects of pore structure and water absorption on internal curing efficiency of porous aggregates. *Constr. Build. Mater.* **2018**, *163*, 949–959. [CrossRef]
72. Castro, J.; Keiser, L.; Golias, M.; Weiss, W. Absorption and desorption properties of fine lightweight aggregate for application to internally cured concrete mixtures. *Cem. Concr. Compos.* **2011**, *33*, 1001–1008. [CrossRef]
73. Lura, P.; Wyrzykowski, M.; Tang, C.; Lehmann, E. Internal curing with lightweight aggregate produced from biomass-derived waste. *Cem. Concr. Res.* **2014**, *59*, 24–33. [CrossRef]

74. ASTM C1761. *Standard Specification for Lightweight Aggregate for Internal Curing of Concrete*; ASTM International: West Conshohocken, PA, USA, 2017. [CrossRef]
75. Yang, S.; Wang, L. Effect of Internal Curing on Characteristics of Self-Compacting Concrete by Using Fine and Coarse Lightweight Aggregates. *J. Mater. Civ. Eng.* **2017**, *29*, 04017186. [CrossRef]
76. Zou, D.; Weiss, W. Early age cracking behavior of internally cured mortar restrained by dual rings with different thickness. *Constr. Build. Mater.* **2014**, *66*, 146–153. [CrossRef]
77. Kamal, M.; Safan, M.; Bashandy, A.; Khalil, A. Experimental investigation on the behavior of normal strength and high strength self-curing self-compacting concrete. *J. Build. Eng.* **2018**, *16*, 79–93. [CrossRef]
78. Mousa, M.I.; Mahdy, M.G.; Abdel-Reheem, A.H.; Yehia, A.Z. Physical properties of self-curing concrete (SCUC). *HBRC J.* **2015**, *11*, 167–175. [CrossRef]
79. Mousa, M.I.; Mahdy, M.G.; Abdel-Reheem, A.H.; Yehia, A.Z. Mechanical properties of self-curing concrete (SCUC). *HBRC J.* **2015**, *11*, 311–320. [CrossRef]
80. Ghourchian, S.; Wyrzykowski, M.; Lura, P.; Shekarchizadeh, M.; Ahmadi, B. An investigation on the use of zeolite aggregates for internal curing of concrete. *Constr. Build. Mater.* **2013**, *40*, 135–144. [CrossRef]
81. Zhutovsky, S.; Kovler, K.; Bentur, A. Autogenous curing of high-strength concrete using pre-soaked pumice and perlite sand. In Proceedings of the 3rd International Research Seminar, Lund, Sweden, 14–15 June 2002; pp. 161–173.
82. Şahmaran, M.; Lachemi, M.; Hossain, K.M.; Li, V.C. Internal curing of engineered cementitious composites for prevention of early age autogenous shrinkage cracking. *Cem. Concr. Res.* **2009**, *39*, 893–901. [CrossRef]
83. Kim, H.-K.; Jang, J.; Choi, Y.; Lee, H. Improved chloride resistance of high-strength concrete amended with coal bottom ash for internal curing. *Constr. Build. Mater.* **2014**, *71*, 334–343. [CrossRef]
84. Wyrzykowski, M.; Ghourchian, S.; Sinthupinyo, S.; Chitvoranund, N.; Chintana, T.; Lura, P. Internal curing of high performance mortars with bottom ash. *Cem. Concr. Compos.* **2016**, *71*, 1–9. [CrossRef]
85. Kim, H.-K.; Lee, H. Hydration kinetics of high-strength concrete with untreated coal bottom ash for internal curing. *Cem. Concr. Compos.* **2018**, *91*, 67–75. [CrossRef]
86. Nguyen, T.; Saengsoy, W.; Tangtermsirikul, S. Influence of Bottom Ashes with Different Water Retainabilities on Properties of Expansive Mortars and Expansive Concretes. *Eng. J.* **2019**, *23*, 107–123. [CrossRef]
87. Rahmasari, B.F.N.; Yang, J.; Yu, Y. Overview of the influence of internal curing in recycled aggregate concrete. In *Sustainable Buildings and Structures: Building a Sustainable Tomorrow*; CRC Press: Boca Raton, FL, USA, 2019; p. 32. [CrossRef]
88. Wang, J.; Liu, F. Internal curing using perforated cenospheres. In Proceedings of the International Concrete Sustainability Conference, Washington, DC, USA, 15 May 2016; pp. 1–13.
89. Chen, P.; Wang, J.; Wang, L.; Xu, Y. Perforated cenospheres: A reactive internal curing agent for alkali activated slag mortars. *Cem. Concr. Compos.* **2019**, *104*, 103351. [CrossRef]
90. Liu, Z.; Zhao, K.; Tang, Y.; Hu, C. Preparation of a Cenosphere Curing Agent and Its Application to Foam Concrete. *Adv. Mater. Sci. Eng.* **2019**, *2019*, 1–9. [CrossRef]
91. van Tuan, N.; Ye, G.; van Breugel, K.; Copuroglu, O. Hydration and microstructure of ultra high performance concrete incorporating rice husk ash. *Cem. Concr. Res.* **2011**, *41*, 1104–1111. [CrossRef]
92. Amin, M.N.; Hissan, S.; Shahzada, K.; Khan, K.; Bibi, T. Pozzolanic Reactivity and the Influence of Rice Husk Ash on Early-Age Autogenous Shrinkage of Concrete. *Front. Mater.* **2019**, *6*, 1–13. [CrossRef]
93. Gupta, S.; Kua, H.W. Effect of water entrainment by pre-soaked biochar particles on strength and permeability of cement mortar. *Constr. Build. Mater.* **2018**, *159*, 107–125. [CrossRef]
94. Mrad, R.; Chehab, G. Mechanical and Microstructure Properties of Biochar-Based Mortar: An Internal Curing Agent for PCC. *Sustainability* **2019**, *11*, 2491. [CrossRef]
95. de Sensale, G.R.; Ribeiro, A.B.; Gonçalves, A. Effects of RHA on autogenous shrinkage of Portland cement pastes. *Cem. Concr. Compos.* **2008**, *30*, 892–897. [CrossRef]
96. Lura, P.; Jensen, O.M.; van Breugel, K. Autogenous shrinkage in high-performance cement paste: An evaluation of basic mechanisms. *Cem. Concr. Res.* **2003**, *33*, 223–232. [CrossRef]
97. Bentz, D.; Snyder, K. Protected paste volume in concrete: Extension to internal curing using saturated lightweight fine aggregate. *Cem. Concr. Res.* **1999**, *29*, 1863–1867. [CrossRef]
98. Zhutovsky, S.; Kovler, K.; Bentur, A. Revisiting the protected paste volume concept for internal curing of high-strength concretes. *Cem. Concr. Res.* **2011**, *41*, 981–986. [CrossRef]
99. Suzuki, M.; Meddah, M.S.; Sato, R. Use of porous ceramic waste aggregates for internal curing of high-performance concrete. *Cem. Concr. Res.* **2009**, *39*, 373–381. [CrossRef]
100. Sato, R.; Shigematsu, A.; Nukushina, T.; Kimura, M. Improvement of Properties of Portland Blast Furnace Cement Type B Concrete by Internal Curing Using Ceramic Roof Material Waste. *J. Mater. Civ. Eng.* **2011**, *23*, 777–782. [CrossRef]
101. Corinaldesi, V.; Moriconi, G. Recycling of rubble from building demolition for low-shrinkage concretes. *Waste Manag.* **2010**, *30*, 655–659. [CrossRef] [PubMed]
102. Silva, R.; de Brito, J.; Dhir, R. Prediction of the shrinkage behavior of recycled aggregate concrete: A review. *Constr. Build. Mater.* **2015**, *77*, 327–339. [CrossRef]

103. Memon, R.P.; Mohd, A.R.B.; Awang, A.Z.; Huseien, G.F.; Memon, U. A review: Mechanism, materials and properties of self-curing concrete. *ARPN J. Eng. Appl. Sci.* **2018**, *13*, 1–13.
104. Suwan, T.; Wattanachai, P. Properties and Internal Curing of Concrete Containing Recycled Autoclaved Aerated Lightweight Concrete as Aggregate. *Adv. Mater. Sci. Eng.* **2017**, *2017*, 1–11. [CrossRef]
105. Zou, D.; Zhang, H.; Wang, Y.; Zhu, J.; Guan, X. Internal curing of mortar with low water to cementitious materials ratio using a normal weight porous aggregate. *Constr. Build. Mater.* **2015**, *96*, 209–216. [CrossRef]
106. Buchholz, F.L.; Graham, T. *Modern Superabsorbent Polymer Technology*; Wiley-VCH: New York, NY, USA, 1998.
107. Jensen, O.M.; Hansen, P.F. Water-entrained cement-based materials: I. Principles and theoretical background. *Cem. Concr. Res.* **2001**, *31*, 647–654. [CrossRef]
108. Esteves, L.P.; Cachim, P.; Ferreira, V.M. Mechanical properties of cement mortars with superabsorbent polymers. In *Advances in Construction Materials 2007*; Springer: Berlin/Heidelberg, Germany, 2007; pp. 451–462. [CrossRef]
109. Siramanont, J.; Vichit-Vadakan, W.; Siriwatwechakul, W. The impact of SAP structure on the effectiveness of internal curing. In *International RILEM Conference on Use of Superabsorbent Polymers and Other New Additives in Concrete*; RILEM Publications SARL: Bagneux, France, 2010; pp. 1–10.
110. Mechtcherine, V.; Wyrzykowski, M.; Schröfl, C.; Snoeck, D.; Lura, P.; De Belie, N.; and Igarashi, S.I. Application of super absorbent polymers (SAP) in concrete construction—update of RILEM state-of-the-art report. *Mater. Struct.* **2021**, *54*, 1–20. [CrossRef]
111. Dang, J.; Zhao, J.; Du, Z. Effect of Superabsorbent Polymer on the Properties of Concrete. *Polymers* **2017**, *9*, 672. [CrossRef]
112. Dudziak, L.; Mechtcherine, V.; Hempel, S. Mitigating early age shrinkage of Ultra-High Performance Concrete by using Super Absorbent Polymers (SAP). In Proceedings of the Creep, Shrinkage and Durability Mechanics of Concrete and Concrete Structures, Ise-Shima, Japan, 30 September–2 October 2008; pp. 847–853.
113. Craeye, B.; Geirnaert, M.; de Schutter, G. Super absorbing polymers as an internal curing agent for mitigation of early-age cracking of high-performance concrete bridge decks. *Constr. Build. Mater.* **2011**, *25*, 1–13. [CrossRef]
114. Snoeck, D.; Jensen, O.; de Belie, N. The influence of superabsorbent polymers on the autogenous shrinkage properties of cement pastes with supplementary cementitious materials. *Cem. Concr. Res.* **2015**, *74*, 59–67. [CrossRef]
115. Wehbe, Y.; Ghahremaninezhad, A. Combined effect of shrinkage reducing admixtures (SRA) and superabsorbent polymers (SAP) on the autogenous shrinkage, hydration and properties of cementitious materials. *Constr. Build. Mater.* **2017**, *138*, 151–162. [CrossRef]
116. Tu, W.; Zhu, Y.; Fang, G.; Wang, X.; Zhang, M. Internal curing of alkali-activated fly ash-slag pastes using superabsorbent polymer. *Cem. Concr. Res.* **2019**, *116*, 179–190. [CrossRef]
117. Mönnig, S.; Lura, P. Superabsorbent Polymers—An Additive to Increase the Freeze-Thaw Resistance of High Strength Concrete. In *Advances in Construction Materials 2007*; Grosse, C.U., Ed.; Springer: Berlin/Heidelberg, Germany, 2007; pp. 351–358. [CrossRef]
118. Wong, H.S. Concrete with Superabsorbent Polymer. In *Eco-efficient Repair and Rehabilitation of Concrete Infrastructures*; Pacheco-Torgal, F., Melchers, R.E., Shi, X., de Belie, N., Van Tittelboom, K., Sáez, A., Eds.; Woodhead Publishing: Sawston, Cambridge, UK, 2018; pp. 467–499.
119. Kim, J.S.; Schlangen, E. Super absorbent polymers to stimulate self healing in Ecc. In Proceedings of the International Symposium on Service Life Design for Intrastructures (SLD2010), Delft, The Netherlands, 4–6 October 2010; pp. 849–858.
120. Ding, H.; Zhang, L.; Zhang, P. Factors Influencing Strength of Super Absorbent Polymer (SAP) Concrete. *Trans. Tianjin Univ.* **2017**, *23*, 245–257. [CrossRef]
121. Wang, F.; Yang, J.; Cheng, H.; Wu, J.; Liang, X. Study on Mechanism of Desorption Behavior of Saturated Superabsorbent Polymers in Concrete. *ACI Mater. J.* **2015**, *112*, 463–469. [CrossRef]
122. Snoeck, D.; Pel, L.L.; de Belie, N. The water kinetics of superabsorbent polymers during cement hydration and internal curing visualized and studied by NMR. *Sci. Rep.* **2017**, *7*, 1–14. [CrossRef]
123. Lee, H.X.D.; Wong, H.S.; Buenfeld, N.R. Potential of superabsorbent polymer for self-sealing cracks in concrete. *Adv. Appl. Ceram.* **2010**, *109*, 296–302. [CrossRef]
124. Chand, M.S.R.; Kumar, P.R.; Giri, P.S.N.R.; Kumar, G.R. Performance and microstructure characteristics of self-curing self-compacting concrete. *Adv. Cem. Res.* **2018**, *30*, 451–468. [CrossRef]
125. El Wakkad, N.Y.; Heiza, H.; Eladly, A. Review on self-curing Concrete. In Proceedings of the 11th International Conference on Nano Technology in Construction, Sharm El-Sheikh, Egypt, 22–25 March 2019; pp. 1–16.
126. Alberty, R.A.; Daniels, F. *Physical Chemestry*, 5th ed.; John Wiley and Sons Ltd.: New York, NY, USA, 1975.
127. Thrinath, G.; Kuma, P.S. Eco-friendly Self-curing Concrete Incorporated with Polyethylene Glycol as Self-curing Agent. *Int. J. Eng.* **2017**, *30*, 473–478. [CrossRef]
128. Mohr, B.J.; Premenko, L.; Nanko, H.; Kurtis, K.E. Examination of wood-derived powders and fibers for internal curing of cement-based materials. In Proceedings of the 4th International Seminar: Self-Desiccation and Its Importance in Concrete Technology, Atlanta, GA, USA, 20 June 2005; pp. 229–244.
129. Mohr, B.J. Durability of Pulp Fiber-Cement Composites. Ph.D. Thesis, Georgia Institute of Technology, Atlanta, GA, USA, 2005. [CrossRef]
130. Elsaid, A.; Dawood, M.; Seracino, R.; Bobko, C. Mechanical properties of kenaf fiber reinforced concrete. *Constr. Build. Mater.* **2011**, *25*, 1991–2001. [CrossRef]

131. Mezencevova, A.; Garas, V.; Nanko, H.; Kurtis, K.E. Influence of Thermomechanical Pulp Fiber Compositions on Internal Curing of Cementitious Materials. *J. Mater. Civ. Eng.* **2012**, *24*, 970–975. [CrossRef]
132. Wu, N.; Hubbe, M.A.; Rojas, O.; Park, S. Permeation of polyelectrolytes and other solutes into the pore spaces of water-swollen cellulose: A review. *Bioresources* **2009**, *4*, 1222–1262. [CrossRef]
133. Wolfenden, A.; Cahn, R.W. *Concise Encyclopedia of Building and Construction Materials*; MIT Press: Cambridge, MA, USA, 1991.
134. Lindstroem, T.; Carlsson, G. The effect of carboxyl groups and their ionic form during drying on the hornification of cellulose fibers. *Sven. Papp.* **1982**, *85*, 146–151.
135. Scallan, A.M. The effect of acidic groups on the swelling of pulps: A review. *Tappi J.* **1983**, *66*, 73–75.
136. Bendzalova, M.; Pekarovicova, A.; Kokta, B.; Chen, R. Accessibility of swollen cellulosic fibers. *Cellul. Chem. Technol.* **1996**, *30*, 19–32.
137. Ahmed, M.Z. Evaluation of Moisture Content in Wood Fiber and Recommendation of the Best Method for Its Determination. Master's Thesis, Helwan University, Cairo, Egypt, 2006; pp. 1–27.
138. Ma, X.; Liu, J.; Shi, C. A review on the use of LWA as an internal curing agent of high performance cement-based materials. *Constr. Build. Mater.* **2019**, *218*, 385–393. [CrossRef]
139. Castro, J.; de La Varga, I.; Weiss, J. Using Isothermal Calorimetry to Assess the Water Absorbed by Fine LWA during Mixing. *J. Mater. Civ. Eng.* **2012**, *24*, 996–1005. [CrossRef]
140. Balapour, M.; Zhao, W.; Garboczi, E.J.; Oo, N.Y.; Spatari, S.; Hsuan, Y.G.; Billen, P.; Farnam, Y. Potential use of lightweight aggregate (LWA) produced from bottom coal ash for internal curing of concrete systems. *Cem. Concr. Compos.* **2020**, *105*, 103428. [CrossRef]
141. Joudah, Z.H.; Huseien, G.F.; Samadi, M.; Lim, N.H.A.S. Sustainability evaluation of alkali-activated mortars incorporating industrial wastes. *Mater. Today Proc.* **2021**, *46*, 1971–1977. [CrossRef]
142. Kikuchi, M.; Miura, T.; Dosho, Y.; Narikawa, M. Application of recycled aggregate concrete for structural concrete: Part 1-Experimental study on the quality of recycled aggregate and recycled aggregate concrete. In Proceedings of the International Symposium organised by the Concrete Technology Unit, London, UK, 11–12 November 1998; pp. 55–68.
143. Matias, D.; de Brito, J.; Rosa, A.; Pedro, D. Mechanical properties of concrete produced with recycled coarse aggregates–Influence of the use of superplasticizers. *Constr. Build. Mater.* **2013**, *44*, 101–109. [CrossRef]
144. Piérard, J.; Pollet, V.; Cauberg, N. Mitigating autogenous shrinkage in HPC by internal curing using superabsorbent polymers. In Proceedings of the International RILEM Conference Volume Changes Hardening Concrete: Testing Mitigation, Lyngby, Denmark, 20–23 August 2006; pp. 97–106. [CrossRef]
145. Raoufi, K.; Schlitter, J.; Bentz, D.; Weiss, W. Parametric Assessment of Stress Development and Cracking in Internally Cured Restrained Mortars Experiencing Autogenous Deformations and Thermal Loading. *Adv. Civ. Eng.* **2011**, *2011*, 1–16. [CrossRef]
146. Costa, H.; Júlio, E.; Lourenço, J. New approach for shrinkage prediction of high-strength lightweight aggregate concrete. *Constr. Build. Mater.* **2012**, *35*, 84–91. [CrossRef]
147. Iffat, S.; Manzur, T.; Noor, M.A. Durability performance of internally cured concrete using locally available low cost LWA. *KSCE J. Civ. Eng.* **2017**, *21*, 1256–1263. [CrossRef]
148. Hossain, T.; Salam, A.; Kader, M.A. Pervious concrete using brick chips as coarse aggregate: An experimental study. *J. Civ. Eng.* **2012**, *40*, 125–137.
149. Zhang, J.; Wang, Q.; Zhang, J. Shrinkage of internal cured high strength engineered cementitious composite with pre-wetted sand-like zeolite. *Constr. Build. Mater.* **2017**, *134*, 664–672. [CrossRef]
150. Chen, F.; Wu, K.; Ren, L.; Xu, J.; Zheng, H. Internal Curing Effect and Compressive Strength Calculation of Recycled Clay Brick Aggregate Concrete. *Materials* **2019**, *12*, 1815. [CrossRef]
151. Lura, P. *Autogenous Deformation and Internal Curing of Concrete*; IOS Press: Amsterdam, The Netherlands, 2003; pp. 1–180.
152. Agostini, F.; Davy, C.; Skoczylas, F.; Dubois, T. Effect of microstructure and curing conditions upon the performance of a mortar added with Treated Sediment Aggregates (TSA). *Cem. Concr. Res.* **2010**, *40*, 1609–1619. [CrossRef]
153. Jensen, O.M.; Hansen, P.F. Water-entrained cement-based materials: II. Experimental observations. *Cem. Concr. Res.* **2002**, *32*, 973–978. [CrossRef]
154. Song, C.; Choi, Y.C.; Choi, S. Effect of internal curing by superabsorbent polymers–Internal relative humidity and autogenous shrinkage of alkali-activated slag mortars. *Constr. Build. Mater.* **2016**, *123*, 198–206. [CrossRef]
155. Shen, D.; Wang, X.; Cheng, D.; Zhang, J.; Jiang, G. Effect of internal curing with super absorbent polymers on autogenous shrinkage of concrete at early age. *Constr. Build. Mater.* **2016**, *106*, 512–522. [CrossRef]
156. Liu, J.; Farzadnia, N.; Khayat, K.H.; Shi, C. Effects of SAP characteristics on internal curing of UHPC matrix. *Constr. Build. Mater.* **2021**, *280*, 122530. [CrossRef]
157. Shen, D.; Liu, C.; Jiang, J.; Kang, J.; Li, M. Influence of super absorbent polymers on early-age behavior and tensile creep of internal curing high strength concrete. *Constr. Build. Mater.* **2020**, *258*, 120068. [CrossRef]
158. Lei, X.; Wang, R.; Jiang, H.; Xie, F.; Bao, Y. Effect of Internal Curing with Superabsorbent Polymers on Bond Behavior of High-Strength Concrete. *Adv. Mater. Sci. Eng.* **2020**, *2020*, 1–13. [CrossRef]

159. Mechtcherine, V.; Gorges, M.; Schroefl, C.; Assmann, A.; Brameshuber, W.; Ribeiro, A.B.; Cusson, D.; Custódio, J.; da Silva, E.F.; Ichimiya, K.; et al. Effect of internal curing by using superabsorbent polymers (SAP) on autogenous shrinkage and other properties of a high-performance fine-grained concrete: Results of a RILEM round-robin test. *Mater. Struct.* **2013**, *47*, 541–562. [CrossRef]
160. Hasholt, M.T.; Jensen, O.M.; Kovler, K.; Zhutovsky, S. Can superabsorent polymers mitigate autogenous shrinkage of internally cured concrete without compromising the strength? *Constr. Build. Mater.* **2012**, *31*, 226–230. [CrossRef]
161. Snoeck, D.; Schaubroeck, D.; Dubruel, P.; de Belie, N. Effect of high amounts of superabsorbent polymers and additional water on the workability, microstructure and strength of mortars with a water-to-cement ratio of 0.50. *Constr. Build. Mater.* **2014**, *72*, 148–157. [CrossRef]
162. Rizzuto, J.P.; Kamal, M.; Elsayad, H.; Bashandy, A.; Etman, Z.; Roos, M.N.A.; Shaaban, I.G. Effect of self-curing admixture on concrete properties in hot climate conditions. *Constr. Build. Mater.* **2020**, *261*, 119933. [CrossRef]
163. Mousa, M.I.; Mahdy, M.G.; Abdel-Reheem, A.H.; Yehia, A.Z. Self-curing concrete types; water retention and durability. *Alex. Eng. J.* **2015**, *54*, 565–575. [CrossRef]
164. Vaisakh, G.; Kumar, M.S.R.; Bala, P.S. An experimental study on properties of M50 concrete cured using PEG 400. *Int. J. Civ. Eng. Technol.* **2018**, *9*, 725–732.
165. Erk, K.A.; Bose, B. *Using Polymer Science to Improve Concrete: Superabsorbent Polymer Hydrogels in Highly Alkaline Environments*; American Chemical Society (ACS): Washington, DC, USA, 2018; pp. 333–356.
166. Bentur, A.; Igarashi, S.-I.; Kovler, K. Prevention of autogenous shrinkage in high-strength concrete by internal curing using wet lightweight aggregates. *Cem. Concr. Res.* **2001**, *31*, 1587–1591. [CrossRef]
167. Lura, P.; Bentz, D.P.; Lange, D.A.; Kovler, K.; Bentur, A. Pumice aggregates for internal water curing. In *Concrete Science and Engineering-A Tribute to Arnon Bentur, Proceedings of the International RILEM Symposium 2004, Evanston, IL, USA, 22–24 March 2004*; National Institute of Standards and Technology: Gaithersburg, MD, USA, 2004; pp. 137–151. [CrossRef]
168. Liu, J.; Shi, C.; Farzadnia, N.; Ma, X. Effects of pretreated fine lightweight aggregate on shrinkage and pore structure of ultra-high strength concrete. *Constr. Build. Mater.* **2019**, *204*, 276–287. [CrossRef]
169. Ji, T.; Zheng, D.-D.; Chen, X.-F.; Lin, X.-J.; Wu, H.-C. Effect of prewetting degree of ceramsite on the early-age autogenous shrinkage of lightweight aggregate concrete. *Constr. Build. Mater.* **2015**, *98*, 102–111. [CrossRef]
170. Golias, M.; Castro, J.; Weiss, W. The influence of the initial moisture content of lightweight aggregate on internal curing. *Constr. Build. Mater.* **2012**, *35*, 52–62. [CrossRef]
171. Zhuang, Y.-Z.; Zheng, D.-D.; Ng, Z.; Ji, T.; Chen, X.-F. Effect of lightweight aggregate type on early-age autogenous shrinkage of concrete. *Constr. Build. Mater.* **2016**, *120*, 373–381. [CrossRef]
172. Henkensiefken, R. Internal Curing in Cementitious Systems Made with Saturated Lightweight Aggregate. Ph.D. Thesis, Purdue University, West Lafayette, IN, USA, 2008.
173. Lura, P.; Bisschop, J. On the origin of eigenstresses in lightweight aggregate concrete. *Cem. Concr. Compos.* **2004**, *26*, 445–452. [CrossRef]
174. Zhutovsky, S.; Kovler, K. Effect of internal curing on durability-related properties of high performance concrete. *Cem. Concr. Res.* **2012**, *42*, 20–26. [CrossRef]
175. Huang, Z.; Wang, J. Effects of SAP on the performance of UHPC. *Bull. China Ceram. Soc.* **2012**, *21*, 539–544.
176. Esteves, L.P. Internal Curing in Cement-Based Materials. Ph.D. Thesis, Universidade de Aveiro, Aveiro, Portugal, 2009.
177. Igarashi, S.; Watanabe, A. Experimental study on prevention of autogenous deformation by internal curing using super-absorbent polymer particles. In Proceedings of the International RILEM conference on volume changes of hardening concrete: Testing and mitigation, Lyngby, Denmark, 20 August 2006; pp. 77–86.
178. Browning, J.; Darwin, D.; Reynolds, D.; Pendergrass, B. Lightweight aggregate as internal curing agent to limit concrete shrinkage. *ACI Mater. J.* **2011**, *108*, 638–644.
179. Wang, F.; Zhou, Y.; Peng, B.; Liu, Z.; Hu, S. Autogenous Shrinkage of Concrete with Super-Absorbent Polymer. *ACI Mater. J.* **2009**, *106*, 123–127. [CrossRef]
180. Assmann, A.; Reinhardt, H. Tensile creep and shrinkage of SAP modified concrete. *Cem. Concr. Res.* **2014**, *58*, 179–185. [CrossRef]
181. Kong, X.-M.; Zhang, Z.-L.; Lu, Z.-C. Effect of pre-soaked superabsorbent polymer on shrinkage of high-strength concrete. *Mater. Struct.* **2014**, *48*, 2741–2758. [CrossRef]
182. Sathanandham, T.; Gobinath, R.; Naveenprabhu, M.; Gnanasundar, S.; Vajravel, K.; Sabariraja, G.; Manoj, R.; Jagathishprabu, R. Preliminary Studies of Self Curing Concrete with the Addition of Polyethylene Glycol. *Int. J. Eng. Res. Technol.* **2013**, *2*, 313–323.
183. Amin, M.; Zeyad, A.M.; Tayeh, B.A.; Agwa, I.S. Engineering properties of self-cured normal and high strength concrete produced using polyethylene glycol and porous ceramic waste as coarse aggregate. *Constr. Build. Mater.* **2021**, *299*, 124243. [CrossRef]
184. Bashandy, A.A.; Meleka, N.N.; Hamad, M.M. Comparative study on the using of PEG and PAM as curing agents for self-curing concrete. *Chall. J. Concr. Res. Lett.* **2017**, *8*, 1–10. [CrossRef]
185. Liu, X.; Chia, K.S.; Zhang, M.-H. Water absorption, permeability, and resistance to chloride-ion penetration of lightweight aggregate concrete. *Constr. Build. Mater.* **2011**, *25*, 335–343. [CrossRef]
186. Elsharief, A.; Cohen, M.D.; Olek, J. Influence of lightweight aggregate on the microstructure and durability of mortar. *Cem. Concr. Res.* **2005**, *35*, 1368–1376. [CrossRef]

187. Sun, X.; Zhang, B.; Dai, Q.; Yu, X. Investigation of internal curing effects on microstructure and permeability of interface transition zones in cement mortar with SEM imaging, transport simulation and hydration modeling techniques. *Constr. Build. Mater.* **2015**, *76*, 366–379. [CrossRef]
188. Al-Fasih, M.Y.; Huseien, G.F.; Ibrahim, I.S.B.; Sam, A.R.; Algaifi, H.A.; Alyousef, R. Synthesis of rubberized alkali-activated concrete: Experimental and numerical evaluation. *Constr. Build. Mater.* **2021**, *303*, 124526. [CrossRef]
189. Zhang, M.-H.; Gjerv, O.E. Microstructure of the interfacial zone between lightweight aggregate and cement paste. *Cem. Concr. Res.* **1990**, *20*, 610–618. [CrossRef]
190. Holm, T.A.; Ooi, O.S.; Bremner, T.W. Moisture dynamics in lightweight aggregate and concrete. In Proceedings of the Theodore Bremner Symposium on High-Performance Lightweight Concrete, Sixth CANMET/ACI International Conference on Durability of Concrete, Thessalonikē, Greece, 1–7 June 2003; pp. 167–184.
191. Bentz, D.P.; Stutzman, P.E. Curing, Hydration, and Microstructure of Cement Paste. *ACI Mater. J.* **2006**, *103*, 348–356. [CrossRef]
192. Wang, F.; Yang, J.; Hu, S.; Li, X.; Cheng, H. Influence of superabsorbent polymers on the surrounding cement paste. *Cem. Concr. Res.* **2016**, *81*, 112–121. [CrossRef]
193. Yang, J.; Wang, F.; He, X.; Su, Y. Pore structure of affected zone around saturated and large superabsorbent polymers in cement paste. *Cem. Concr. Compos.* **2019**, *97*, 54–67. [CrossRef]
194. Ma, X.; Zhang, J.; Liu, J. Review on superabsorbent polymer as internal curing agent of high performance cement-based material. *J. Chin. Ceram. Soc.* **2015**, *43*, 1099–1110. [CrossRef]
195. Liu, J.; Farzadnia, N.; Shi, C. Effects of superabsorbent polymer on interfacial transition zone and mechanical properties of ultra-high performance concrete. *Constr. Build. Mater.* **2020**, *231*, 117142. [CrossRef]
196. Ridi, F.; Fratini, E.; Baglioni, P. Cement: A two-thousand-year-old nano-colloid. *J. Colloid Interface Sci.* **2011**, *357*, 255–264. [CrossRef]
197. Safiuddin, M.; Alengaram, U.J.; Rahman, M.; Salam, A.; Jumaat, M.Z. Use of Recycled Concrete Aggregate in Concrete: A Review. *J. Civ. Eng. Manag.* **2013**, *19*, 796–810. [CrossRef]
198. Xiao, J.; Li, W.; Fan, Y.; Huang, X. An overview of study on recycled aggregate concrete in China (1996–2011). *Constr. Build. Mater.* **2012**, *31*, 364–383. [CrossRef]
199. Tabsh, S.W.; Abdelfatah, A.S. Influence of recycled concrete aggregates on strength properties of concrete. *Constr. Build. Mater.* **2009**, *23*, 1163–1167. [CrossRef]
200. He, J.; Kawasaki, S.; Achal, V. The Utilization of Agricultural Waste as Agro-Cement in Concrete: A Review. *Sustainability* **2020**, *12*, 6971. [CrossRef]
201. Shafigh, P.; Bin Mahmud, H.; Jumaat, M.Z.; Zargar, M. Agricultural wastes as aggregate in concrete mixtures–A review. *Constr. Build. Mater.* **2014**, *53*, 110–117. [CrossRef]
202. El-Dieb, A.S.; El-Maaddawy, T.A.; Mahmoud, A.A.M. Water-soluble polymers as self-curing agents in cement mixes. *Adv. Cem. Res.* **2012**, *24*, 291–299. [CrossRef]
203. Gopi, R.; Revathi, V. Flexural behavior of self-curing concrete with lightweight aggregates. *Mater. Today: Proc.* **2021**, *45*, 2449–2455.
204. Alaskar, A.; Alshannag, M.; Higazey, M. Mechanical properties and durability of high-performance concrete internally cured using lightweight aggregates. *Constr. Build. Mater.* **2021**, *288*, 122998. [CrossRef]
205. Pradeep, P.; Beenamol, H.S. Effect of pre-soaked light expanded clay aggregate on strength, durability and flexural behaviour of high-performance concrete. *J. Eng. Sci. Technol.* **2019**, *14*, 2629–2642.
206. Savva, P.; Nicolaides, D.; Petrou, M.F. Internal curing for mitigating high temperature concreting effects. *Constr. Build. Mater.* **2018**, *179*, 598–604. [CrossRef]