Possibilities for the application of agro- industrial wastes in cementitious materials: A brief review of the Brazilian perspective

de Azevedo, Afonso R. G.; Amin, Mohamed; Hadzima- Nyarko, Marijana; Agwa, Ibrahim Saad; Zeyad, Abdullah M.; Tayeh, Bassam A.; Adesina, Adeyemi

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Review on effect of steam curing on behavior of concrete

Abdullah M. Zeyad [a,b,*], Bassam A. Tayeh [c], Adeyemi Adesina [d], Afonso R.G. de Azevedo [e], Mohamed Amin [f], Marijana Hadzima-Nyarko [g], Ibrahim Saad Agwa [f]

[a] *Civil Engineering Department, Faculty of Engineering, Jazan University, Jazan, Saudi Arabia*
[b] *Department of Civil Engineering, Faculty of Engineering, University of Science and Technology, Aden, Yemen*
[c] *Civil Engineering Department, Faculty of Engineering, Islamic University of Gaza, Palestine*
[d] *Department of Civil and Environmental Engineering, University of Windsor, Windsor, Canada*
[e] *Civil Engineering Laboratory – LECIV, State University of the Northern Rio de Janeiro – UENF, Brazil*
[f] *Civil and Architectural Constructions Department, Faculty of Technology and Education, Suez University, Egypt*
[g] *Faculty of Civil Engineering and Architecture Osijek, Josip Juraj Strossmayer, University of Osijek, V. Preloga 3, 31000 Osijek, Croatia*

A R T I C L E I N F O

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A B S T R A C T

Steam curing at atmospheric pressure is a method used to raise concrete strength at early ages. The steam curing method is based on the application of hot water vapor at a temperature between 40 °C and 100 °C for a limited period. The highest temperatures and the longest curing period are determined based on the characteristics of the target concrete, the cost, and the production cycle. This study presents the effect of steam curing regime application on concrete properties. Steam curing has a negative effect on the microstructure of concrete, and this effect increases with higher temperatures. The curing period and the precuring period in addition to the cooling period influence the properties and the strength of concrete. This study summarizes the previous literature related to the effect of steam curing regime application on the properties of concrete. Previous studies confirm that concrete exposed to steam curing regime at low temperatures ranging between 45 °C and 80 °C and a longer period within a 24-hour cycle achieve better concrete properties. In addition, raising the steam curing temperatures above 80 °C has a negative effect on concrete microstructure and other concrete properties in general. This study also concludes that adding pozzolanic or complementary cement materials contributes to reducing the damage resulting from the application of steam curing regime on concrete at later ages. Such verification is required to clarify the behavior of concrete under the influence of steam curing systems, understand their effect on the properties of concrete, and look for ways to reduce the damage from degrees of application of steam curing regime.

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* Corresponding author.

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1. Introduction

Concrete curing refers to the procedures used to provide sufficient moisture to continue cement hydration enhancement. Concrete curing controls temperature and humidity, inside and outside the concrete (ACI, 2001; Mi et al., 2018). Continuous curing of cement allows the hydration to continue, resulting in 1) increased gel formation (calcium silicate hydrate), 2) increased strength, 3) reduced pore size, and 4) reduced plastic and dry shrinkage of concrete. However, interrupting the curing of concrete adversely influences all those properties (Amin et al., 2021; Wyrzykowski and Lura, 2016). Maintaining proper internal humidity is critical because cement hydration stops when the relative humidity inside the capillary drops below 80% (Jensen, 1995). Insufficient internal humidity and complete hydration of the cement will not occur, and the resulting concrete may not have the required strength and impermeability (Patel et al., 1988). In addition, a continuous porous structure that contacts the concrete surface may be produced, allowing the entry of harmful elements (liquid and gases) from the surrounding environment and possibly causing various problems in durability (Niu et al., 2020). Moreover, early drying of concrete leads to the appearance of micro cracks resulting from the plastic shrinkage, which may expand to be visible in all parts of concrete (Mauroux et al., 2012). In addition, water evaporation and moisture loss reduce the initial water–cement ratio, resulting in incomplete hydration of cement compounds and reducing the quality of concrete (Taylor, 2014). Various factors lead to rapid evaporation of concrete water such as wind speed, relative humidity, atmospheric temperature, water–cement ratio in the mixture, type of cement, aggregates, and additives used in the mixture (Zeyad, 2019; Askar et al., 2017). The evaporation of the mixing water in the initial stage causes plastic shrinkage cracks and in the final stage causes dry shrinkage cracks (Cohen et al., 1990). Therefore, maintaining the moisture content of the concrete elements is critical to the continuation of the cement hydration and the prevention of damage resulting from drying out. Curing methods for concrete are mainly to maintain the moisture content within the concrete elements through a) preventing evaporation, b) reducing the evaporation rate, and c) compensating concrete for evaporating water (Saliba et al., 2011). Several curing methods applied to concrete may suit certain conditions, and the most common are (Kosmatka et al., 2008) 1) covering concrete surfaces with wet cloth or wet burlap, 2) water sprinklers or water mist, 3) immersing concrete surfaces with water (pools), 4) the membrane method, 5) the concrete insulation method, and 6) steam curing (hydration acceleration).

Concrete becomes high performance with a proper curing period, making it more impermeable and resistant to aggressive environments (Zain et al., 2000). In OPC concrete, improvement is rapid at the early ages and continues to improve over later ages. Fig. 1 shows the effect of moist curing time on the strength of concrete. When curing stops, the strength of concrete continues to evolve for a short period and then stops after the relative humidity in the interior of the concrete drops to less than 80% (Jensen, 1995; Kosmatka et al., 2002). However, resuming the humid treatment may lead to the development of concrete strength again but may not achieve the target strength. Thus, continuously curing concrete from the time of casting is best such that sufficient internal moisture is maintained for cement hydration to proceed and to gain strength and durability (Kosmatka et al., 2002; Neville, 2002; Targan et al., 2003; Eldagal and Elmukhtar, 2008).

Furthermore, curing concrete at low temperatures slows down the cement hydration rate compared with curing at high temperatures. Several researchers reported that concrete cured at temperatures below 23 °C is (Kosmatka et al., 2002) unfavorable for the development of early strength (Kjellsen and Detwiler, 1992). The increase in curing temperatures would lead to an increase in the strength at an early age. However, it may decrease the 28-day strength, as shown in Fig. 2.

Three main methods are used for curing concrete while maintaining a suitable humidity within the proper temperature:

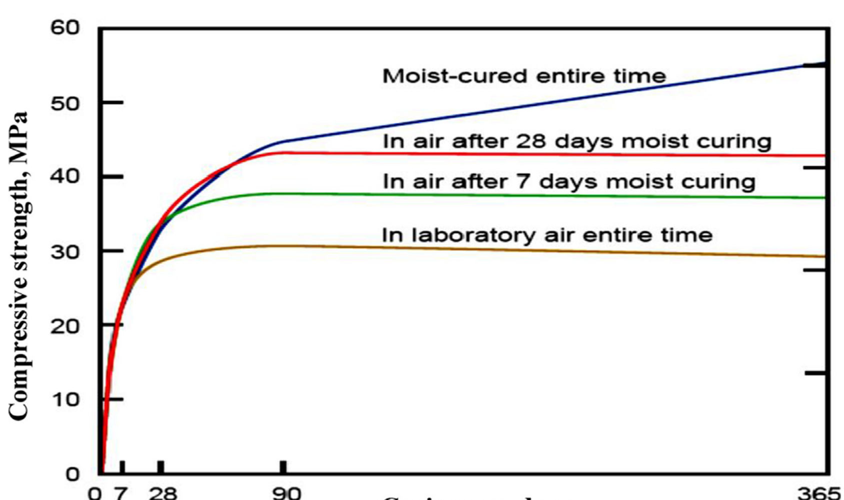


Fig. 1. Effect of moist curing time on strength of concrete (Kosmatka et al., 2002).

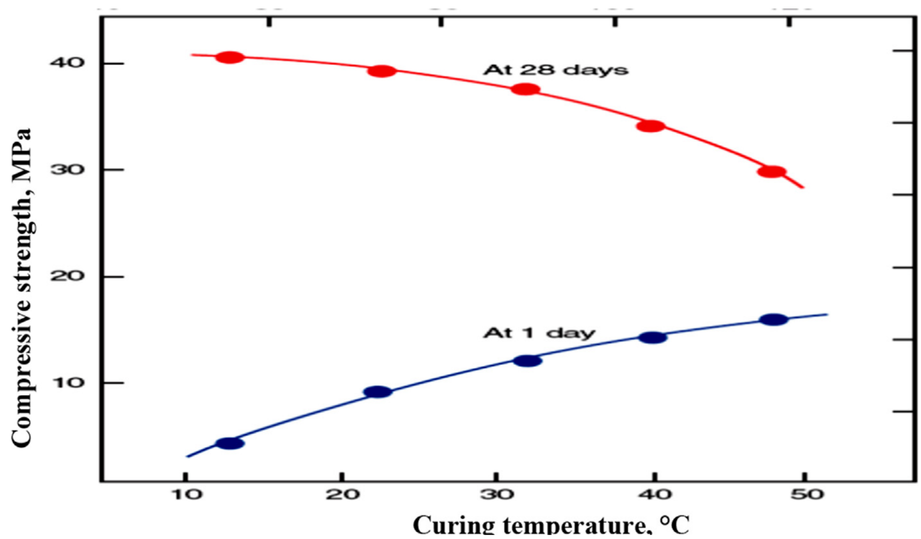


Fig. 2. Effect of curing temperature on strength of concrete (Kosmatka et al., 2002).

1. The mixing water is maintained during the hardening of concrete at an early age until the required properties of concrete are achieved. This method can be accomplished using suitable means such as water immersion, spraying, fogging, or saturated wet coverings.
2. The loss of mixing water is reduced because of evaporation on the surface of the concrete. It can be overcome by covering concrete with impervious paper or plastic sheets, or applying a membrane curing compound.
3. The acquisition of strength is accelerated by the provision of heat with high humidity at the early age of concrete by employing treatment methods such as steam curing at atmospheric pressure or steam curing at high pressure (autoclaving) (Kosmatka et al., 2002; Neville, 2002; Ramachandran, 1995).

This study highlights the effect of steam curing regimes on the performance of concrete. Steam curing is heat curing with a high moisture content, and it is used to accelerate cement hydration under atmospheric pressure. Thus, the strength of concrete products is developed in a short time. The gain of strength can be accelerated by steam curing concrete at specified temperatures because the rate of cement hydration increases with increasing temperature and period of curing. Steam curing is a special case of wet curing, in which steam involves the supply of water to concrete under atmospheric pressure. Water vapor is generated at atmospheric pressure because of water heating, and the temperature is less than 100 ˚C.

2. Steam curing at atmospheric pressure

Curing of concrete by steam at atmospheric pressure accelerates compressive strength development and improves the properties of concrete at early ages. The gain in early strength can be increased manifold by curing in steam, as a result of the increase rate of cement hydration with the increase in the temperature. Under atmospheric pressure at temperatures below 100 ˚C, steam curing can be regarded as hot moist curing that enables a vapor-saturated supply of water and high relative humidity. Turkel and Alabas (Turkel and Alabas, 2005) reported temperatures of steam curing for concrete ranging between 40 ˚C and 100 ˚C. A higher steam curing temperature (80 ˚C–100 ˚C) leads to a lower final strength; hence, steam curing temperature is a compromising factor between rate of strength gain at early ages and ultimate strength (Turkel and Alabas, 2005; Soroka et al., 1978). Furthermore, Aydin et al. encouraged the application of heat curing at a

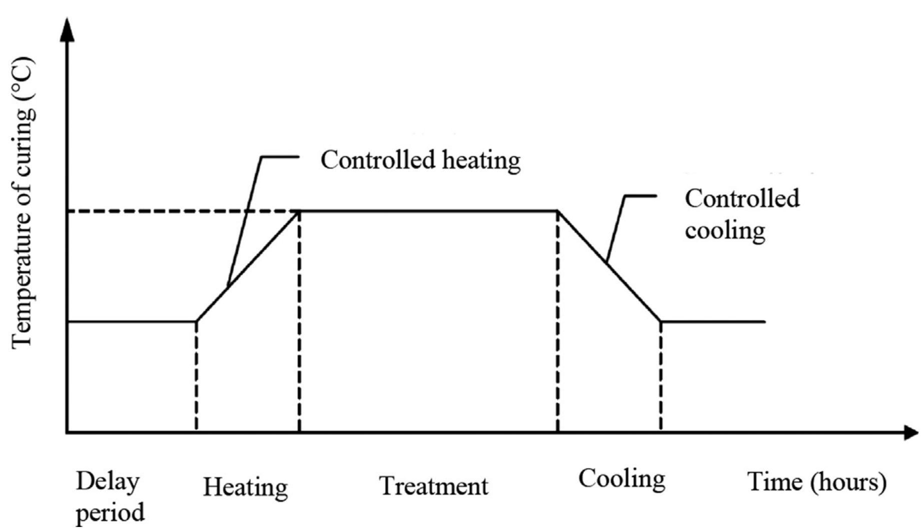


Fig. 3. Schematic representation of steam-curing procedure.

Table 1
Compressive strength of concrete with different delay periods for steam curing (H et al., 2008).

Concrete	Age	Reference concrete	Steam curing hold time (5 h)				Steam curing hold time (10 h)			
			Delay period (hours)							
			3	2	1	I S T	3	2	1	I S T
type	days	Compressive strength (MPa)								
C 25	1	13.7	16.4	16.7	18.2	18.4	17.9	18.9	21.3	22.6
	3	23.4	18.5	19.6	22.3	22.7	19.8	21.1	23.2	24.8
	7	29.5	21.7	20.5	25.2	24.7	22.3	23.0	25.9	26.4
	28	34.1	27.5	28.0	28.7	30.2	28.5	29.5	30.6	32.3
	90	37.5	31.7	33.4	34.5	34.5	32.7	34.2	35.0	36.3
C 40	1	22.6	23.5	24.1	27.4	30.2	26.3	27.7	30.7	34.1
	3	33.8	23.8	26.0	30.4	32.7	27.6	28.1	32.5	35.2
	7	40.9	26.9	28.8	34.6	36.7	29.2	31.2	35.7	38.4
	28	46.1	33.4	34.9	36.5	41.2	36.3	36.8	40.5	42.9
	90	49.2	39.9	42.2	43.0	43.5	42.2	43.4	45.5	46.5

IST is the Initial setting time of the concrete. It is 235 min for C25 and 220 min for C40

medium temperature (60 ˚C–80 ˚C) over a cycle of at least 1 day and 4 h that is more economical and energy efficient (Aydin et al., 2015). It resulted in about 70% gain in strength from the 28-day strength. This gain is sufficient for prefabricated concrete elements and purposes of prestressing. Curing period, curing temperature, and cement type are the important parameters in steam curing. Other factors that affect the strength of concrete are w/b ratio, mineral admixture, and type of curing after steam curing. Curing period and temperature are normally adjusted according to the target (Erdogdu and Kurbetci, 1998; Gambhir, 2004; Sherman et al., 1996).

2.1. Effect of steam curing periods on strength of concrete

A typical steam-curing cycle at atmospheric pressure consists of four stages. Fig. 3 shows the cycle of steam curing for a complete cycle (ACI, 1987; 2001).

2.1.1. Delay period of steam curing

Many researchers indicated that some delay prior to subjecting the concrete to steam is beneficial to concrete properties, such as strength, impenetrability, and durability.

Hanson (1963) reported that increasing the delay period from 1 h to 5 h leads to compressive strength increase at all ages (Hanson). Furthermore, Shideler and Chamberlin (1949) concluded that a delay period of 2–6 h for starting the steam curing leads to an increase of about 15%–40% in strength at the age of one day compared with steam curing started immediately after casting. In addition, Soroka et al. (Soroka et al., 1978) reported that subjecting concrete to steam curing at delay periods between 30 and 60 min would cause a decrease in compressive strength of concrete at later ages (Soroka et al., 1978). Alexandersson (1972) observed that expansion does not happen for delay periods between 4 and 7 h and depending on w/c ratio, no decrease in compressive strength at later ages is observed. Erdem et al. (2003) recommended a delay in the start of steam curing by a period equal to the initial setting time of concrete (Erdem et al., 2003). When the delay period is equal to the initial setting time, higher strengths are obtained, as shown in Table 1. Moreover, the delay period should be between 2 and 5 h to avoid inferior concrete quality. Shorter delay periods can increase porosity and accelerate cracks on account of tensile stresses formed due to the internal pressure in the pores (Neville, 2002; ACI, 1992). Wang (2014) et al. indicated that the application of the 6-hour preheating period results in a high compressive strength of 94 MPa (28 days) under the 60 ˚C curing temperature with an 8-hour curing period, compared with 1 and 3 h for its compressive strengths of 93 and 92 MPa, respectively (Wang et al., 2014). Ramezanianpour (2013) et al. indicated that the application of the preheat period depends on heating temperature and heating period. The preheat period of 1 h had high compressive strengths of 56 and 64 MPa (28 days) under curing temperatures of 50 ˚C and 70 ˚C with curing period of 10 and 12 h, respectively. The 3-hour period before heating resulted in better compressive strength of 63 MPa (28 days) in the case of curing temperature of 60 ˚C and curing period of 10 h. This result makes the setting of the period before heating subject to change based on these parameters (Ramezanianpour et al., 2013). However, researchers stated that relying on the initial sitting time of concrete, as a period before the onset of heating, is better to resolve the difference in the estimate of the period before heating. Zeyad et al. used the initial time of concrete of 3-hour as preheating for all steam curing cycles applied in their research (Zeyad et al., 2021; Zeyad, 2013). This method is consistent with the opinion of many researchers, who reported that the application of short periods before curing can lead to a difference in the thermal expansion coefficients of the concrete components, thus resulting in micro cracking and increased porosity (Mironov, 1966). However, delaying the steam curing cycle for a period equal to the initial setting time remarkably reduces these adverse effects. It also facilitates the reaction of gypsum with tricalcium-aluminate that reduces the solubility of gypsum at higher temperatures (Patel et al., 1995). Although early application of steam curing is a common practice, several researchers here indicated that this is quite harmful and that some delay before exposure to steam is beneficial for concrete properties, such as strength and durability (Erdem et al., 2003; Alexanderson). Erdem et al. indicated (Erdem et al., 2003) that the delay period should be determined in such a way that the steam curing process should not cause expansion. According to Türkelet and Alabas (Türkel and Alabas, 2005), the lower quality of concrete due to the shorter lag time is due to the increased porosity and cracks caused by the tensile stress caused by the internal stress in the pores. Research has been established that concrete must have a critical tensile strength before steam curing begins. Shi et al. (Shi et al., 2020) stated that if steam application is started before the time of the initial setting of the concrete, the outer position (or faces) of the concrete sample hardens early while the inner concrete is still plastic because the concrete temperature lags behind the curing room temperature while the temperature is rising. The inner plastic concrete can expand and induce tensile stress in the rigid outer shell (Wang et al., 2014). Hence, initial setting time has been suggested as a measurable criterion for the delay period before steam treatment is applied.

Heating period

This period can be defined as the time required for raising the heat to the target temperature. This period depends on the difference between temperature of casting and ultimate temperature of steam curing. The ACI 517.2 preferred the rise in the rate of temperature of the steam ranging between 22 ˚C and 44 ˚C per hour. Steven

Table 2
Cycle of steam curing from different sources.

No	Preheating	Rate °C/hr	Ultimate temperature	Duration of ultimate temperature	Cooling °C/hr	Researcher
1	6	15	65	4	–	(Titherington, 1998)
2	6–8	20	65	9	20	(Khalil, 2002)
3	2, 4, 6	15	50, 65, 80	8, 10, 12, 14	15	(Erdogdu and Kurbetci, 1998)
4	3.5,4	22	65	6	22	(Tanaka, et al., 2004)
5	setting time	21	80	5, 10	–	(H et al., 2008)
6	6	20	60	16	6	(Liu et al., 2005)
7	2	20	60	8	40	(Aydın et al., 2005)
8	4	11	65	5	15	(Erdog˘du and Kurbetci, 2005)
9	2, 4, 6	15	50, 60, 80, 95	8, 10, 12, 14	15	(Cassagnabere et al., 2009)
10	3	18	65, 85	4,8,16, 24, 36	11	(Turkel and Alabas, 2005)
11	2.83	10	55	12.5	12	(Najafi Kani and Allahverdi, 2009)
12	–	–	45, 65, 85	5, 10, 15, 20	–	(Cassagnabere et al., 2010)
13	2.83	10	55	12.5	12	(Gesoglu, 2010)
14	2	17	65	17	50	(Ramezanianpour, 2014)
15	2–5	11–33	50–82	–	–	(Neville, 2002)
16	initial set	11–44	58–82	4–12	–	(ACI, 1992)

Table 3
Compressive strength (indicated as % of control) development.

Curing time (hour)	Compressive strength (% of reference concrete)							
	Curing temperature and age							
	65 °C				85 °C			
	3 days	7 days	28 days	56 days	3 days	7 days	28 days	56 days
4	85	82	73	69	103	88	79	75
8	101	87	78	74	112	95	85	81
16	104	89	80	76	114	98	88	83
24	122	105	94	89	108	92	82	78
36	113	97	86	82	108	92	82	78

et al. suggested that the application of a heating rate of 10 °C–20 °C per hour should be used to avoid damage caused by the rapid heating rate; a slow heating rate requires a longer period, and the same time allows a uniform distribution of heat and a greater depth within the concrete samples regularly (Hwang et al., 2012). Hwang et al. indicated the advantage of applying a heating rate of 22 °C per hour to achieve a high early compressive strength, with a maximum steam curing temperature of 60 °C (Yan et al., 2019). Many previous studies applied a heating rate for steam curing ranging of 10 °C–22 °C per hour (Yan et al., 2020; Ferdosian and Camões, 2017; Zeyad et al., 2021; Zhang et al., 1996). Table 2 shows several cycles of steam curing from different sources

Period of fixing ultimate steam curing temperature

The total cycle of steam curing (included in four stages) can be determined based on its suitability to the requirements of compressive strength and the durability of concrete in the early and later ages. It is also subject to economic considerations in terms of long working shifts in concrete production to match the production cycle that satisfies steam curing.

a. Steam curing period

For a satisfactory steam curing cycle of concrete, Neville (2012) suggested a steam curing period of no more than 18 h to complete the total cycle (excluding the delay period). Furthermore, Hanson (1963) suggested a period for the stabilization of the maximum temperature of the steam treatment in the range between 16 and 18 h. Many researchers used different periods of fixing temperature depending on the desired properties of concrete. Torkel and Alabas studied four different periods of 4, 8, 16, 24, and 36 h of maximum stabilization phase at 65 °C and 85 °C. Accordingly, they reported that the highest compressive strength was obtained when the steam curing temperature was stabilized for 24 h at 65 °C and 16 h at 85 °C. The compressive strength rates (indicated as percentage of control) under different curing periods are listed in Table 3, where steam-cured concrete's compressive strength is 22% higher than that of immersion-cured control concrete. Concrete compressive strength curing for 3 days 1 delay at 24 h soaking time at 65 °C. By applying curing at 65 °C for 36 h, it reached 113% of the normal compressive strength cured for 3 days. Steam curing leads to lower compressive strength in the later life. This finding was confirmed in this research, where approximately 28% and 26% decrease in compressive strength were found at the age of 28 days for 24 and 16 h treatment at 65 °C, respectively (Türkel and Alabas, 2005).

Zhang et al. (2021) reported exposing concrete samples to steam curing regimes of three different durations of steam curing, namely, 10, 12, and 14 h, at two different temperatures, 60 °C and 70 °C. In general, the results showed an improvement in compressive strength with the increase in treatment period. At a temperature of 60 °C at the age of 1 day, the obtained compressive strengths were 15.7, 18.7, and 20.2 MPa for steam curing period of 12, 14, and 16 h, respectively, whereas at a temperature of 70 °C at the age of 1 day, the obtained compressive strengths were 18, 20.6, and 22 MPa for stem curing periods of 12, 14, and 16 h, respectively. Erdem et al. (Erdem et al., 2003) concluded that prolonging the steam curing period from 5 h to 10 h achieved compressive strengths of 30.2 and 34.1 MPa, respectively, at a maximum steam curing temperature of 80 °C.

Mindess (2019) indicated that applying a longer period of steam curing of 24 h results in a higher compressive strength than shorter periods of 12 h, and this applies to the early age of 1 day. The length of the curing period negatively affects the compressive strength at the later ages of 90 days, as shown in Figs. 4 and 5.

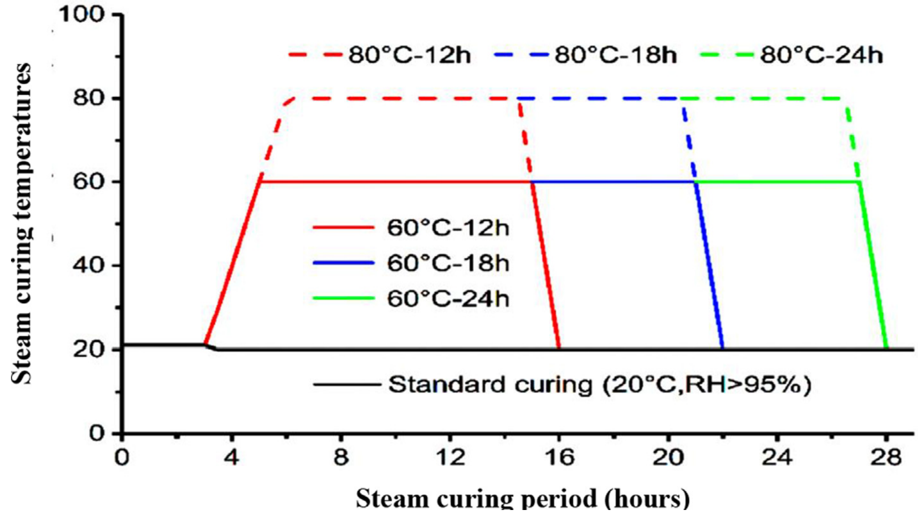


Fig. 4. Scheme of curing regimes for concrete specimens (Mindess, 2019).

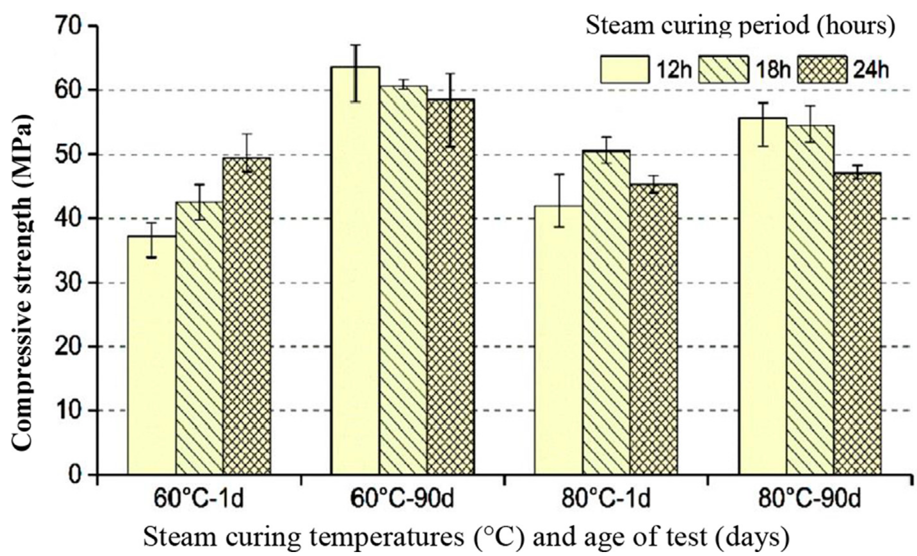


Fig. 5. Compressive strength of concrete with different steam curing regimes (Mindess, 2019).

Table 4
Compressive strength of normal cured and steam-cured concrete specimens (Türkel and Alabas, 2005).

Cement type	Compressive strength (MPa)									Curing temperature (°C)
	Normal curing (days)				Steam curing period (hours)					
	3	7	28	56	4	8	16	24	36	
PC42.5	38.2	44.5	49.8	52.4	36.3	38.6	39.7	46.7	46.7	65
					39.4	42.6	43.6	41.1	41.1	85
PKC/A42.5	36.2	40.9	49.0	52.2	29.8	33.3	34.1	37.6	37.6	65
					33.5	37.8	38.1	39.6	39.7	85

b. Steam curing temperature

The effect of steam curing temperatures is directly reflected on the properties of concrete in the early and late ages. Maximum curing temperatures can vary in the range of 40 °C to 100 °C, whereas optimum temperature is generally between 50 °C and 85 °C (Benammar et al., 2013). Curing temperature is adjusted depending on the need for rate of strength gain and ultimate strength because a high steam curing temperature leads to low strength at later ages (Liu et al., 2020). ACI 517.2R (ACI, 1992) concluded that no remarkable differences in early strengths could be found with cement Type II concretes for maximum steam curing temperatures of 58 °C, 70 °C, or 82 °C. Furthermore, strength of concretes at 28 days under steam curing with temperatures of 70 °C–80 °C led to a slight reduction in strength compared with those steam-cured with temperatures at 48 °C or 50 °C. Yan et al. (2019) described that in general, increases in maximum room temperature can lead to improvements in early mechanical properties. They suggested maximum processing temperatures from 40 °C to 85 °

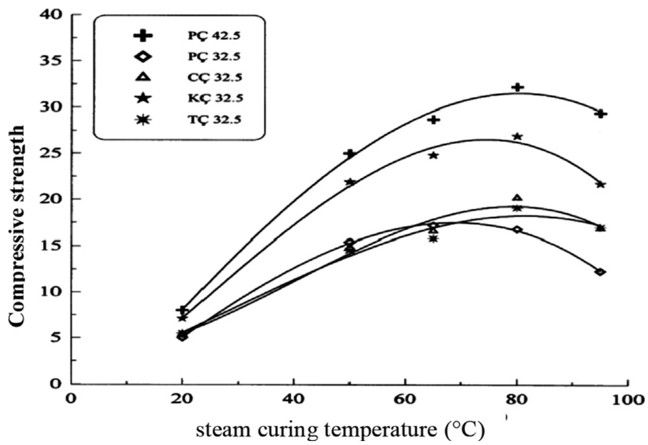


Fig. 6. **a.** One-day compressive strength with respect to curing temperature (Erdogdu and Kurbetci, 1998). **b.** 28-day compressive strength with respect to curing temperature (Erdogdu and Kurbetci, 1998).

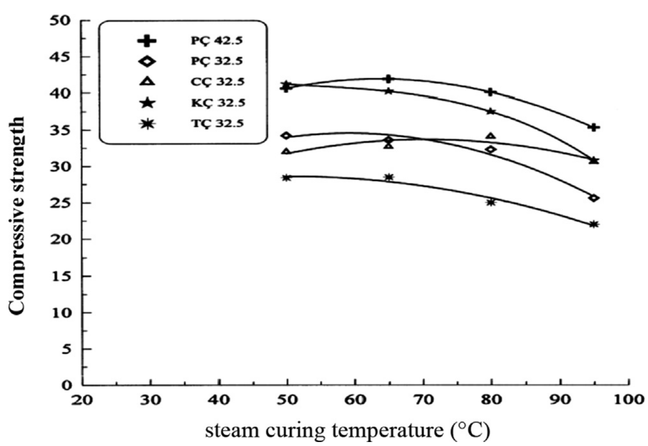


Fig. 6 (*continued*)

C. This wide range of temperatures may be related to the difference in the target properties of compressive strength and permeability as well as the proportions of the mixture and the diversity of chemical and physical properties of the cement and the complementary cement materials used. The temperature limit has been set to mitigate any adverse effect of elevated curing temperatures on the long-term development of the properties of strength and the permeability and the durability of concrete. Turkel and Alabas (Türkel and Alabas, 2005) also showed that increasing the temperature of steam curing from 65 °C to 85 °C helps improve the compression strength of concrete, as shown in Table 4.

Moreover, many researchers reported ample evidence that the increase in temperature of steam curing should be between 65 °C and 85 °C to obtain a higher early strength. Moreover, it should not exceed more than 90 °C because it can cause reduction in the strength of concrete. To minimize the decrease in the strength in the later ages, using the temperature of steam curing between 50 °C and 80 °C is preferred according to Fig. 6a and b (Kosmatka et al., 2002; Erdogdu and Kurbetci, 1998; Gambhir, 2004; Cassagnabere et al., 2009).

2.2.1.4. Period of temperature decrease (Cooling period). This stage is the end of steam curing just before the storage of the samples in water tanks for testing at different ages. The recommendations from ACI 517.2R (ACI, 1992) stated that moderate cooling does not affect the concrete properties, although it provides an additional period to steam curing. By contrast, rapid cooling may cause formation of cracks on the surface of the elements, which may affect strength and other characteristics of concrete. Using rates of cooling equal to the rate of rise in the temperature of steam curing has been the practice of several researchers. Famy et al. (2001) believe that during the cooling of steam curing, a fast cooling rate leads to a difference between the temperature of the interior of the concrete sample and its surface; thus, the tensile stresses due to thermal change will cause cracks. In addition, dispersing moisture from concrete and forming a directional path are easy. Therefore, a higher cooling rate results in higher absorption and sorptivity coefficient. Other researchers support this opinion (Famy et al., 2001; Ioannou et al., 2008; Long et al., 2012; Han et al., 2021).

2.2. Heat transfer into concrete samples under the influence of steam curing

The heat of the steam used for curing is gradually transferred to the concrete samples based on the following factors: maximum steam temperature, steam curing application period, thickness of the concrete sample, and moisture content within the sample. Shi et al. (2020) mentioned that the change in the initial temperature range inside the concrete occurs through the release of the hydration heat of the cement material and from the transfer of heat from the external environment. Then, the change in the internal heat field begins due to the effect of steam treatment. In the stage of raising the temperature, high heat is applied to the edge of the mold and the outer layer of the sample in return for lower temperatures inside the samples. They found a difference of up to 30 °C between the internal temperature and the temperature on the surface of the sample (the dimensions of the sample are 100 * 100 * 100 mm). Thus, under the influence of continuous steam curing and cement hydration processes, internal temperatures begin to exceed the surface temperature of concrete samples, and the difference reaches 17 °C. Fig. 7(a, b, c and d) show the heat transfer within the concrete samples during steam curing in the second, sixth, seventh, and twelfth hours of steam curing, respectively.

Several researchers support that the heat of hydration in addition to the storage of heat transferred from the outside may be higher than the heat on the surface of the concrete samples. Zou et al. (2021) reported that the temperature of hydration increases with the increasing application of steam treatment. Fig. 8 shows the rise in hydration temperature when steam curing is applied (Fig. 9).

Hanif et al. (2017) reported that rising temperatures of steam curing lead to high rates of heat release from cement hydration and a high heat retention within concrete samples.

2.3. Effect of steam curing on cement hydration

Steam curing accelerates cement hydration, microstructure formation, and the acquisition of early strength as well as other mechanical properties (Gallucci et al., 2013). Acceleration of cement hydration by steam curing leads to the transfer of heat and moisture to the concrete samples; thus, temperature and humidity have a direct, complex effect on the field of chemical reactions and the field of thermal stress on the concrete. Accordingly, the process of acquiring rapid hardening of concrete during steam curing has different, complex effects, especially the development of its long-term performance (Baoju et al., 2001; Kjellsen, 1996).

Kjellsen et al. studied the effect of high temperature on the microstructure of hydration products (Cassagnabère et al., 2009; Verbeck; He et al., 2012). They reported that the heterogeneous distribution of water products and the dense water crust are the main reasons for the detrimental effects of steam curing on the long-term performance of concrete. In addition, to speed up the hydration rate of the steam curing, the hydration products are not precipitated and dispersed uniformly in the space between the cement particles. Therefore, a dense layer of C-S-H gels is formed around the cement particles, which hinders further hydration of the cement particles. Han et al.

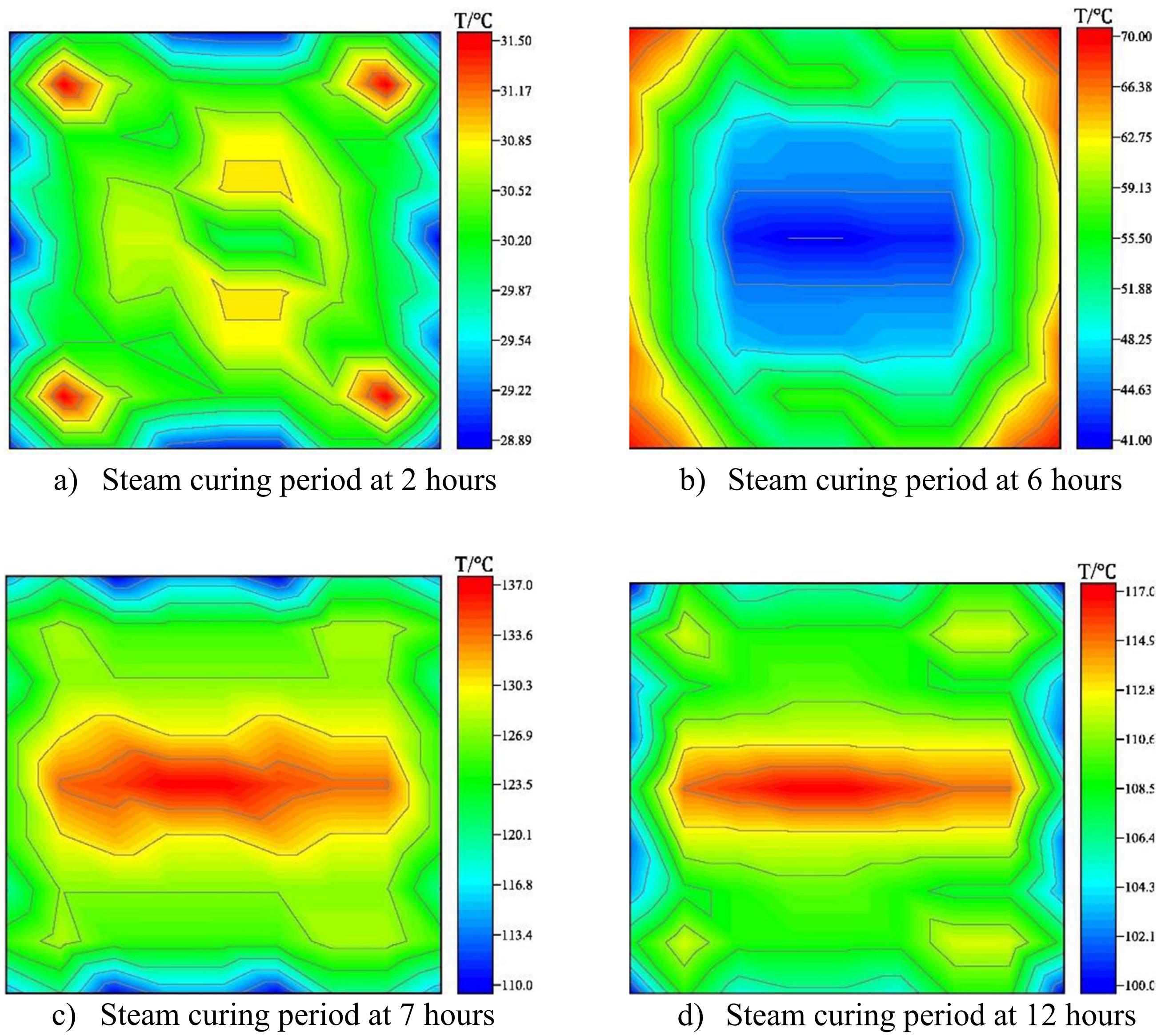


Fig. 7. a, b, c, and d. Distribution of internal temperatures in concrete samples during steam curing (Shi et al., 2020).

(Han et al., 2021; Ma et al., 2017; Detwiler et al., 1994) proved that the presence of thermal damage and steam treatment would cause uneven distribution of hydration products, bulging deformation, and embrittlement. Ba et al. demonstrated the increase in density microstructure of cement paste under the influence of steam curing due to the acceleration of hydration. Fig. 10 shows the microscopic images of steam-cured concrete samples. Most of the completely unreacted cement and fly ash particles are shown in Fig. 5a. With the application of steam curing, the size of the fly ash particles decreases, and the C-S-H gel fraction increases, as shown in Fig. 5b–d. This result indicates that the degree of hydration of the cement and fly ash increases with the duration of steam curing (Fig. 11).

2.4. Effect of steam curing on pore distribution

The increase in temperature during steam curing accelerates the reactions of cement hydration, which produces a high early strength but can adversely affect the strength and properties of concrete in the long-term because the accelerated curing often results in nonuniform distribution of the pore that leads to formation of a coarser pore structure, and the hydration products do not have sufficient time to spread evenly before they harden. The products of hydration hardening result in a dense region around the cement particles and lesser dense regions further away. This result causes the produced structure to be more porous and nonuniform. Moreover, these dense zones can impede further hydration of the encapsulated cement grains. Several measures to reduce the potential negative effects of steam curing are delay in steam curing cycle, rate of temperature rise, maximum temperature fixing, and cooling period (Hooton and Titherington, 2004; Igarashi et al., 2005). Jennings (1988) and Gao et al. (2016) contended that the reasons for the adverse effects of steam curing on concrete are that the later lower strength of steam-cured concrete is related to the pore structure within the cement matrix, which is a direct, crucial factor of the mechanical properties, impermeability, and frost resistance of concrete and abrasion. Understanding the evolution of the pore structure within the cement matrix also helps explain cement paste hydration and the underlying cause of concrete strength and deterioration. Gao et al. (Gao et al., 2017) described pores in concrete as multiscale, and they can be divided into three sections according to the average pore size: 1) microscopic pores, 2) capillary pores, and 3)

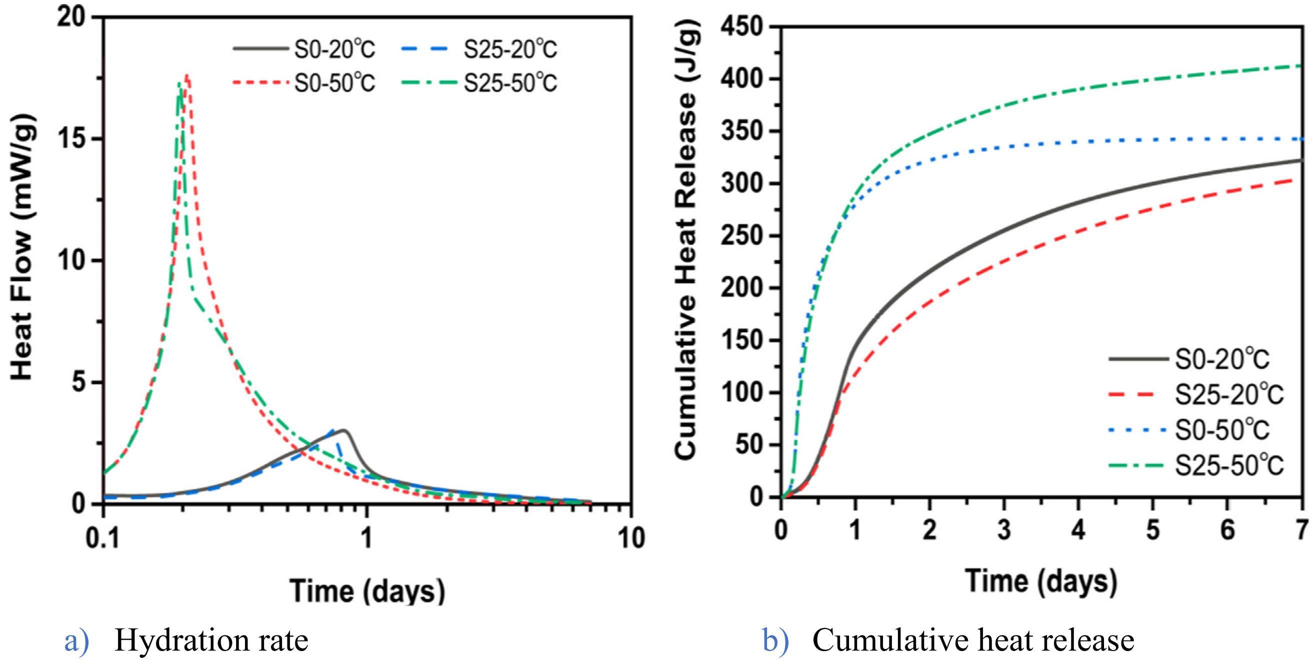


Fig. 8. Hydration rate and cumulative heat release of cement paste with and without slag at different temperatures (Zou, 2021).

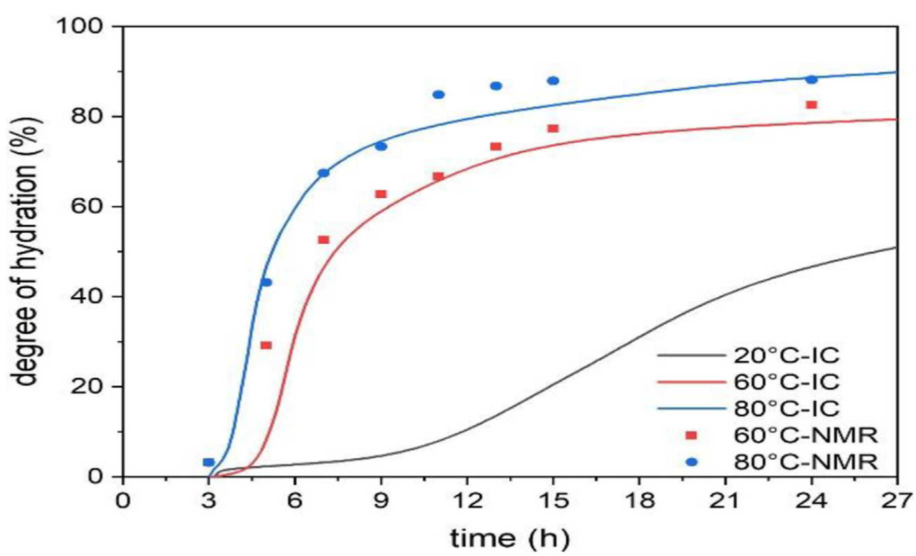
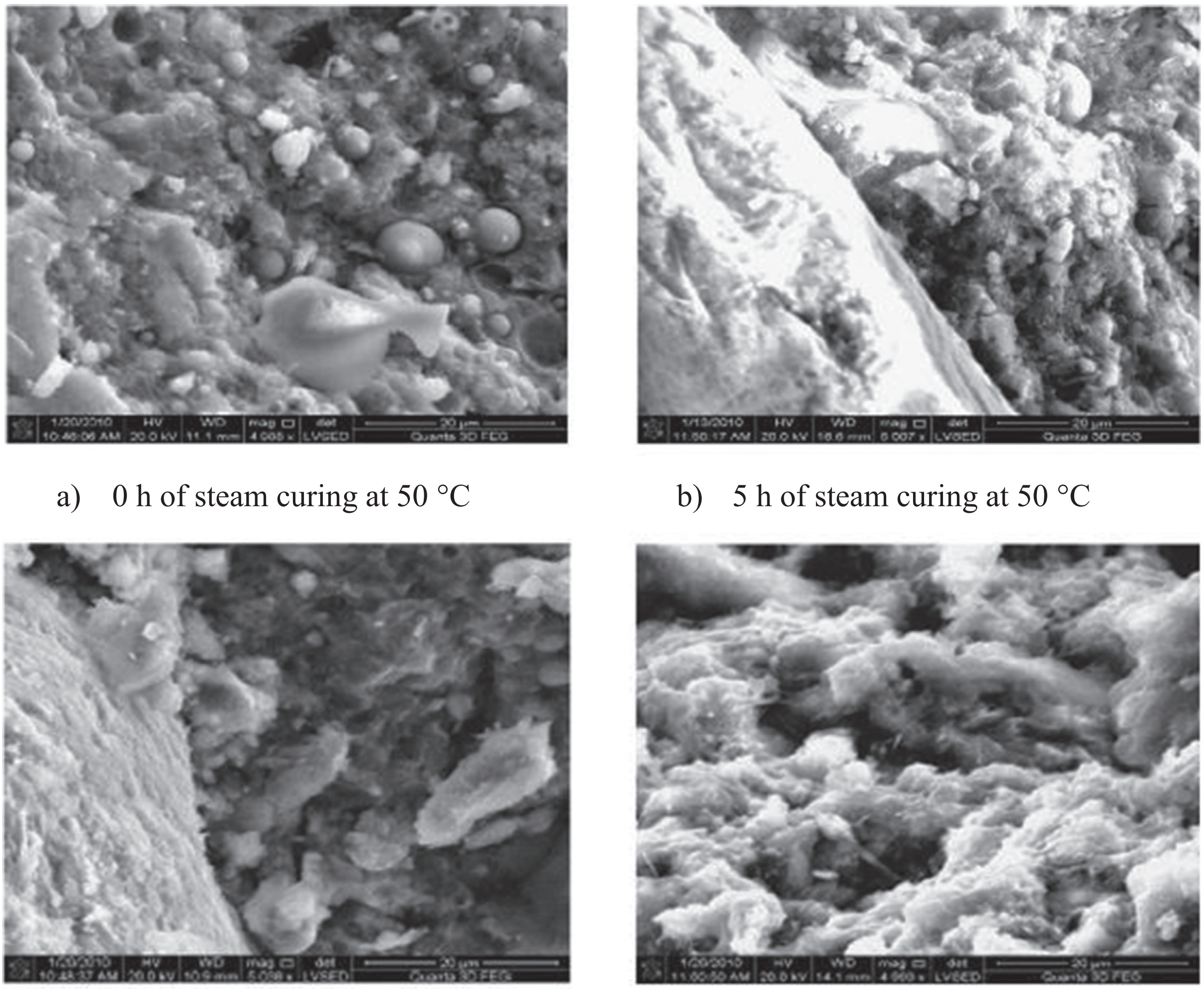


Fig. 9. Comparison of hydration degree of cement paste under different curing temperatures (Hanif, 2017).

gelatinous pores. Macroscopic pores can be seen with the naked eye, including air bubbles and defects caused by the concrete mixing or incomplete air degassing (insufficient vibration). Capillary pores, smaller and larger than 2 μm, appear in cement paste with a high water–cement content, which greatly affects the strength and the permeability of concrete. The pores in the gel are nanometer sized (less than 10 nm) and usually seen as portions of the solid phase in a water–cement paste (Jennings et al., 2007; Francis Young, 1988).

Gallucci et al. (Baoju et al., 2001; Ba et al., 2011) stated that several small pores fuse to form larger pores due to the capillary pressure caused by the rapid precipitation of hydration products and the migration of water vapor produced by the steam treatment. This process leads to a high processing temperature in the case of a volume expansion distortion of the relatively highwater content in the interface transition zone range because the aggregates are surrounded by large amounts of water vapor. Shi et al. (2020) stated that rising water vapor may cause the initial pores between the cement paste and the aggregates not to be easily filled with wetting products. Moreover, during the cooling period of steam curing, water vapor condenses in the self-contained pores, which in turn reduces the pressure inside the pores. This factor is cited as one of the main reasons why high-temperature steam-cured concrete is more brittle than standard-cured concrete. Deschner et al. (2013) and Deschner et al. (2013) explained the effect of treated temperatures on the distribution of pores and the interface transition zone, as shown in Fig. 13. Clearly, the increase in temperature negatively affects the pores, and the sample treated with steam at 75 °C has more pores and an adhesion area weaker with rubble. As the gel becomes loose and the pores and micro cracks spread wetting products after curing temperature rises, the deterioration behavior of steam-cured concrete is more evident.



a) 0 h of steam curing at 50 °C

b) 5 h of steam curing at 50 °C

c) 14 h of steam curing at 50 °C

d) 24 h of steam curing at 50 °C

Fig. 10. SEM photos of concrete under different durations of steam curing.

2.5. Effect of steam curing on volumetric changes of concrete

Volumetric changes during the steam curing stage are caused by several factors: 1) thermal expansion of each concrete stage, 2) chemical shrinkage caused by water, and 3) self-shrinkage due to low internal humidity. Zou et al. (2021) stated that the autogenous shrinkage of steam-curing samples is lower due to the thermal expansion of concrete, In addition, the moisture content inside the samples decreases during steam treatment. By contrast, the volumetric deformation of steam-cured concrete samples appears as expansion (volumetric increase). One of the reasons for volume changes is the delayed formation of Aft and delayed formation causing late volumetric expansion (Taylor et al., 2001). Several studies showed that cement paste contains AFt after a day of standard curing, as nucleation and growth of AFt crystals help complete the reaction between C_3A and gypsum to form AFt within hours of adding water. Cement pastes treated with steam at very high temperatures at 85 °C and above lead to the dissolution of C_3A and gypsum. Steam treatment at 90 °C makes AFt very unstable and rapidly degrade to AFm, SO42−, Ca2+, and Al(OH)4 − once formed. It is then absorbed by C-S-H in large amounts. However, AFm solubility product solubility increases with increasing steam-curing temperature (Tosun, 2006; Zhuang and Sun, 2020; Katsioti et al., 2011). Brunetaud et al. (Brunetaud et al., 2007; Escadeillas et al., 2007; Escalante-Garcia and Sharp, 2001) reported that the delay of AFm in the re-formation of the AFt early after the completion of the steam treatment leads to the occurrence of delayed ettringite formation. In addition, resistance to AFt formation may occur in the solid paste due to the encapsulation and blocking effects of wetting products. Subsequently, the widening may be counted and microcracks are formed on a large scale due to the low crystallization resistance of Aft. Katsioti et al. (2011) reported that expansion approximately stops after 400 days, and steam treatment at 60 °C has an expansion rate at 4 years of approximately 100×10^{-6}, whereas the expansion rate at steam treatment temperature of 90 °C at 4 years reaches 300×10^{-6}, which is three times greater and theoretically increases the risk of fracture. Therefore, late jet formation occurs at steam processing temperatures of up to 90 °C. The deformation values of normal concrete (PC) and high strength concrete (HSC) under the influence of steam curing are shown in Fig. 12.

2.6. Effect of steam curing on strength of concrete containing pozzolan

The application of steam curing to concrete leads to an acceleration of the hydration processes accompanied by a rapid hardening, which causes a less dense structural structure and an uneven distribution of hydration products compared with immersion-cured concrete. It generates a higher porosity, although it increases compressive strength at an early age and causes less force at later ages compared with

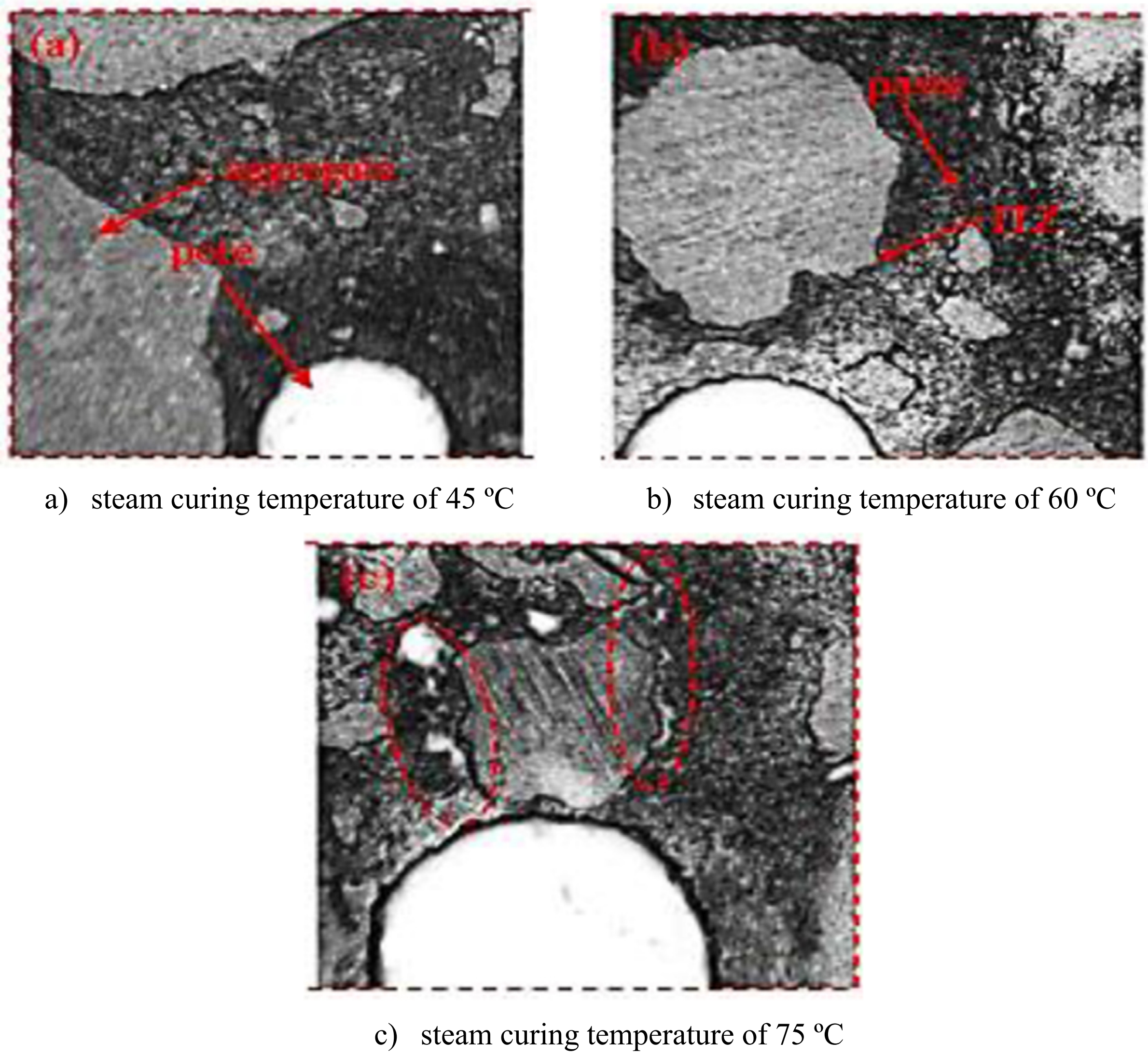


Fig. 11. Typical microscopic images, in which white is identified as pore, grey as aggregate and black as paste, age = 90 days. (Deschner et al., 2013).

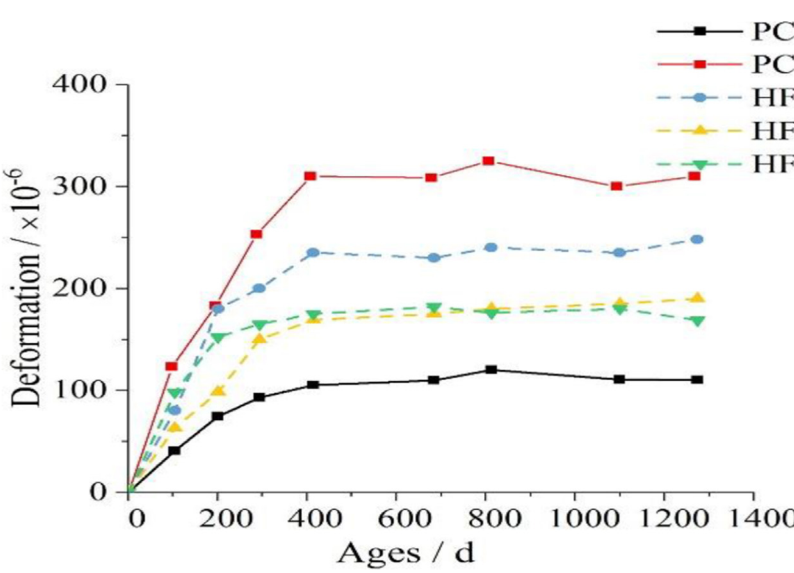


Fig. 12. Deformation values of PC and HSC under the influence of steam curing.

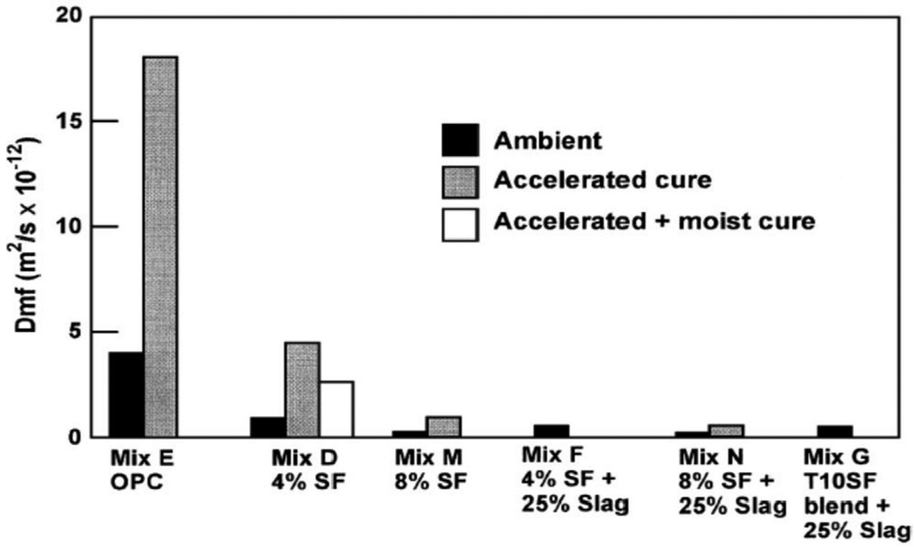


Fig. 13. Effect of cementing materials and curing procedures on steady-state migration results (Igarashi et al., 2005).

immersion-cured concrete (Mo et al., 2021). Several researchers suggested the use of supplementary cement materials to reduce or reduce the effect of steam curing application on concrete at later ages (Zeyad et al., 2021; Zhang et al., 2021; Wang et al., 2019). To mitigate these negative effects of steam curing on concrete, the researchers made several targeted attempts, including extending steam curing time, slowing heating rate, and reducing curing temperature. However, it often conflicts with economic benefits and decomposes property; thus, it is seldom used by factories of prefabricated items (Deschner et al., 2013; Brooks and Al-Kaisi, 1990; Ezziane et al., 2007). Addition of pozzolanic materials also has a remarkably mitigates the adverse effects of steam curing. For example, adding fly ash or ground granulated blast furnace slag to concrete can modify the kinetics of hydration, reduce the heat evolution, and produce C-S-H gel in addition to filling the pores. Ezziane et al. (2007) and Aydin et al. (2015) reported that elevation of temperature and curing period have positive effects on strength at an early age (1 day), and elevation of temperature leads to reduction in ultimate strength. The pozzolanic material starts to contribute to the improvement of strength at a later age by depending on the pozzolanic reaction with Ca $(HO)_2$ (Erdogˇdu and Kurbetci, 2005; Ma et al., 1994; Chen et al., 2019; Ho et al., 2003). Shi et al. confirmed that the addition of supplementary cementitious materials to steam-cured concrete causes an increase in sorptivity coefficient at the age of 28 days and in turn contributes to reducing heat damage due to a delay the rate of hydration of the cement components. Moreover, mixing different types of active supplementary cement materials for steam-cured concrete contributes effectively to reducing the sorptivity coefficient (Shi et al., 2020). Chen et al. reported that incorporating metakaolin allows reducing the maximum steam curing temperature without compromising early strength as well as reducing absorption in the long term. They also revealed that steam-cured concrete containing a mixture of metakaolin and limestone shows improved mechanical properties, less absorbability, and better microstructure compared with steam-cured concrete based on blast furnace slag and fly ash only (Aldea et al., 2000). Many researchers observed that concrete containing supplementary cementitious materials show better performance than Portland cement concrete on application of steam curing. Furthermore, the use of supplementary cementitious materials can prevent deleterious expansions related to delayed ettringite formation, alkali–silica reaction, water sorptivity,

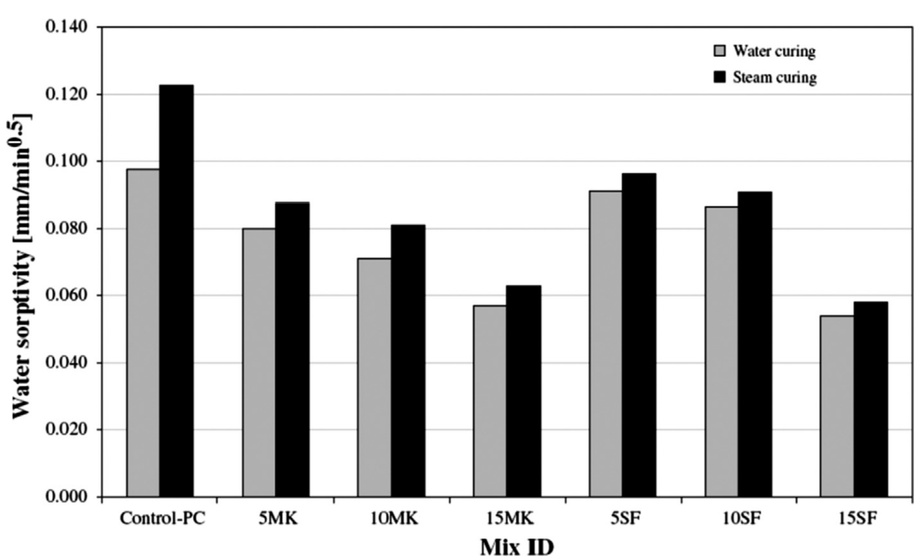


Fig. 14. Effects of curing condition and mineral admixture content on sorptivity of concretes (Ramezanianpour, 2014).

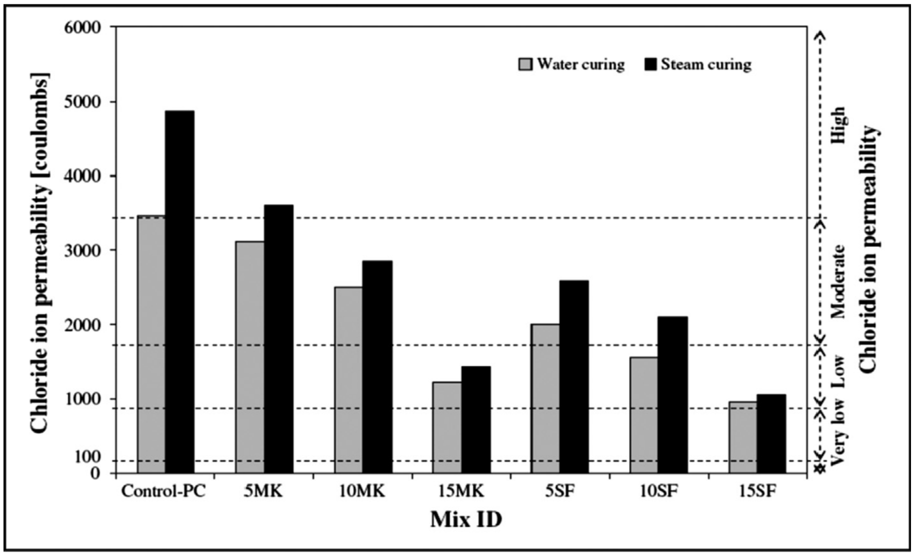


Fig. 15. Effects of curing condition and mineral admixture content on chloride ion permeability of concretes (Ramezanianpour, 2014).

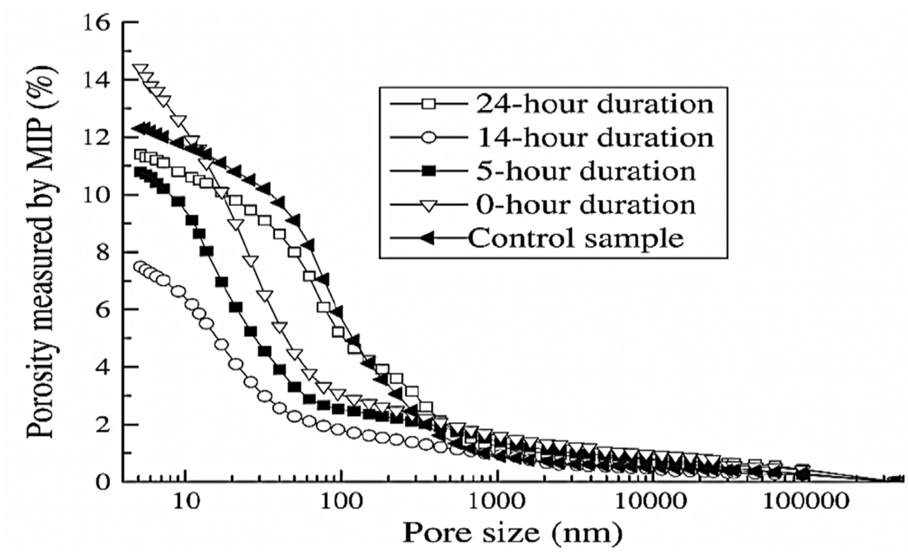


Fig. 16. Pore characteristics measured by MIP (Cassagnabère et al., 2009).

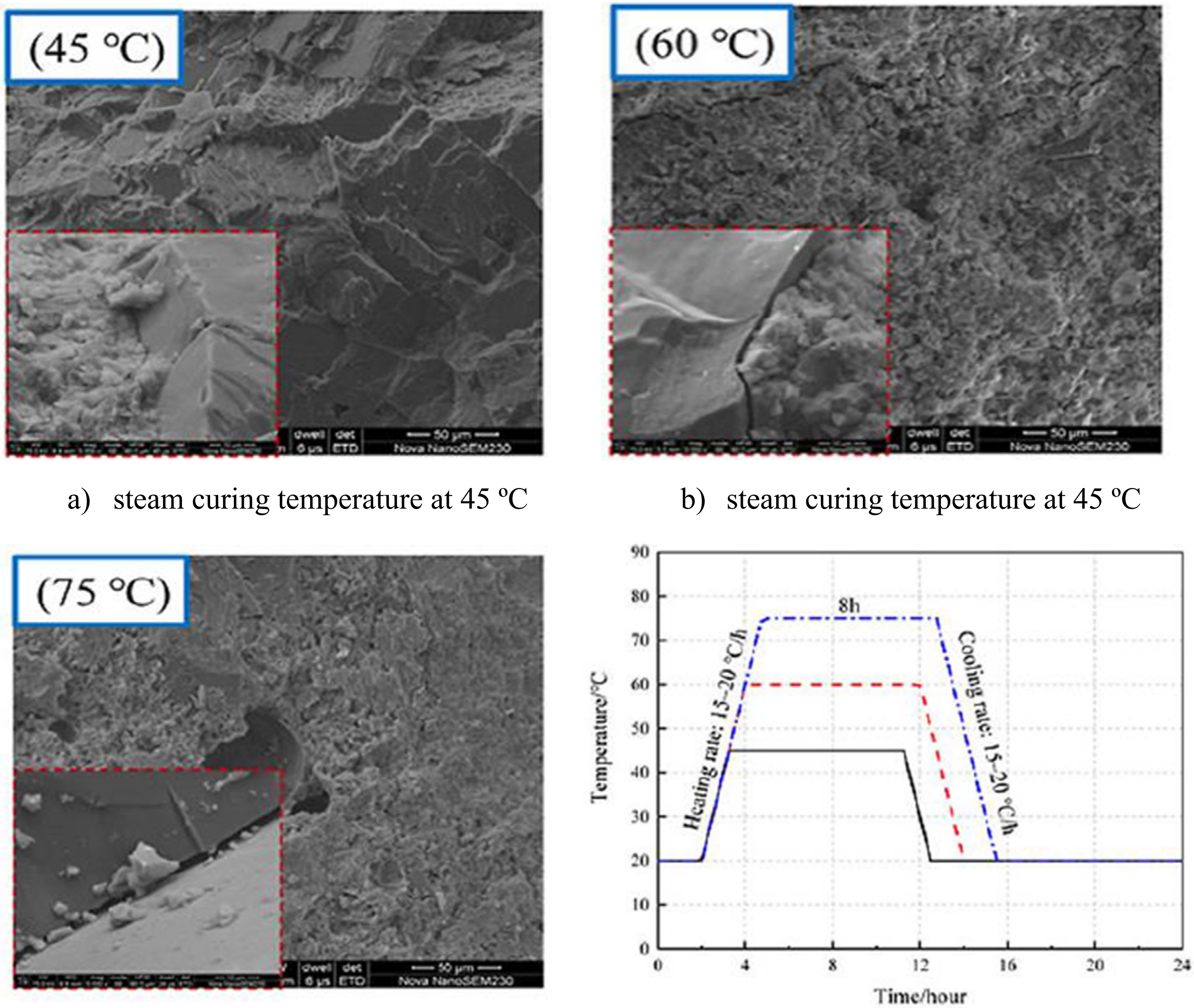
and chloride ion permeability (Aydin et al., 2015; Gesoglu, 2010). Fig. 13 shows that the use of supplementary cementitious materials assists in increasing the chloride penetration resistance of concrete with the use of the steam curing.

Furthermore, many researchers found that adding pozzolanic materials to concrete and using steam treatment leads to improvement in the properties of concrete compared with those of concrete without supplementary cementitious materials or/and that used normal curing. Fig. 14 shows the reduction in water sorptivity when pozzolanic materials are added to concrete. In addition, steam curing leads to a higher chloride permeability than normal curing. The negative effect of steam curing on chloride permeability appears to be lower when pozzolanic material is added to concrete, as shown in Fig. 15 (Ramezanianpour et al., 2014; Acquaye, 2006; Shi et al., 2021).

2.7. Microstructural characteristics

Steam curing accelerates the maturation of cement products. As a result, the steam curing affects the microstructural characteristic and can hamper the proper development of concrete properties at early ages and negatively affect the properties of concrete in later ages. Studies carried out by researchers on the microstructural properties and the hydration of cement pastes subjected to temperatures ranging from 5 °C to 50 °C using back-scattered imaging found that low curing temperatures result in a uniform distribution of hydration products and fine pores. Elevated temperatures result in nonuniformly distributed hydration products and coarser pores (Kjellsen and Detwiler, 1992). Microstructure of hydrated cement paste formed at high curing temperatures affects the strength and transport properties of concrete. The large, interconnected pores resulting from high-temperature curing does not make more durable concrete structures. Furthermore, Fig. 16 shows a decrease in coarser pores when the period of steam curing is increased up to14 h. By contrast, increasing the period up to 24 h results in the increase of coarse pores (Cassagnabère et al., 2009).

Fig. 17 shows the effect of the maximum steam curing temperatures on the permeability of the surface of the concrete samples. The permeability of the sample surface is higher than the permeability of the inner surface of the steam-cured concrete. This finding confirms the thermal effect of steam pretreatment, as mentioned in



a) steam curing temperature at 45 ºC

b) steam curing temperature at 45 ºC

c) steam curing temperature at 75 ºC

d) scheme of steam treatment time and temperature

Fig. 17. Effect of steam curing temperature on surface permeability of concrete and ITZ (Deschner et al., 2013).

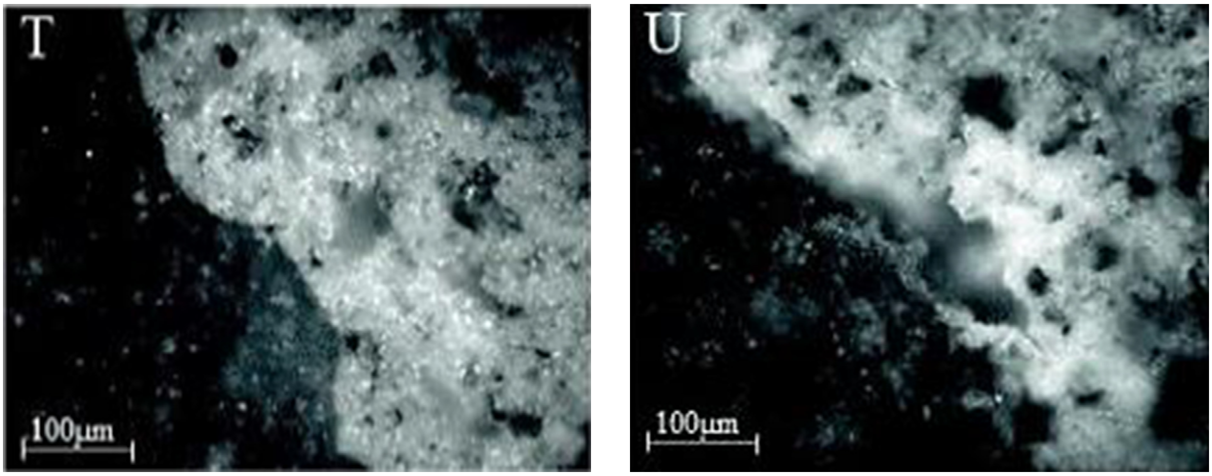
other previous studies. In addition, excessive curing temperatures are detrimental to the long-term impermeability of steam-cured concrete (Deschner et al., 2013).

Shi et al. reported that steam curing at high temperatures results in coarser pores and visible micro cracks in the ITZ in one day. In addition, the temperature discrepancy on and inside the concrete surface during steam curing may lead to substantial stress and increase the deterioration of the concrete surface structure, as illustrated in Fig. 18 (Shi et al., 2021).

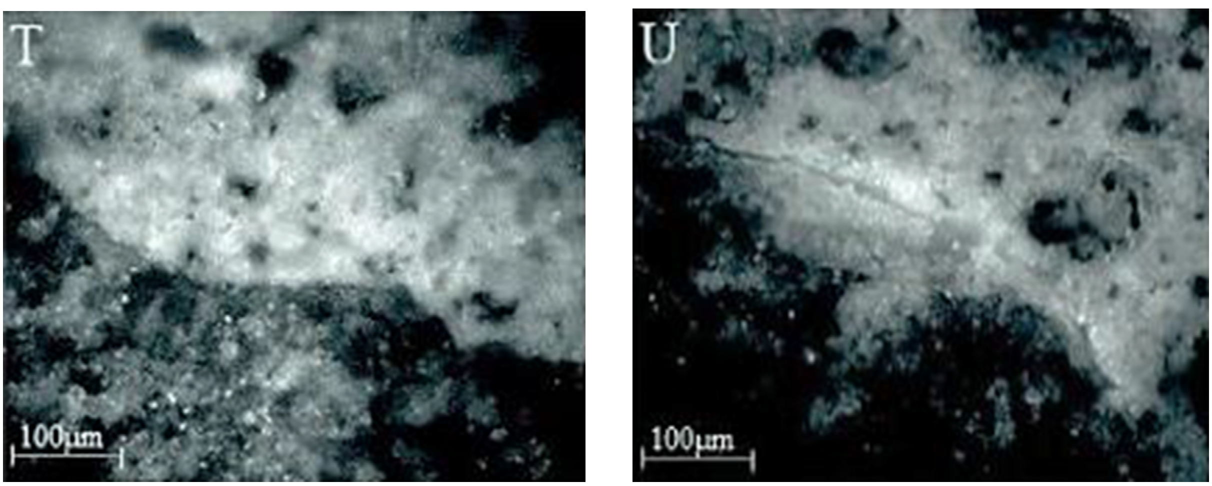
3. Conclusion

This study reports the effects of steam curing on the behavior of concrete. The following conclusions can be drawn:

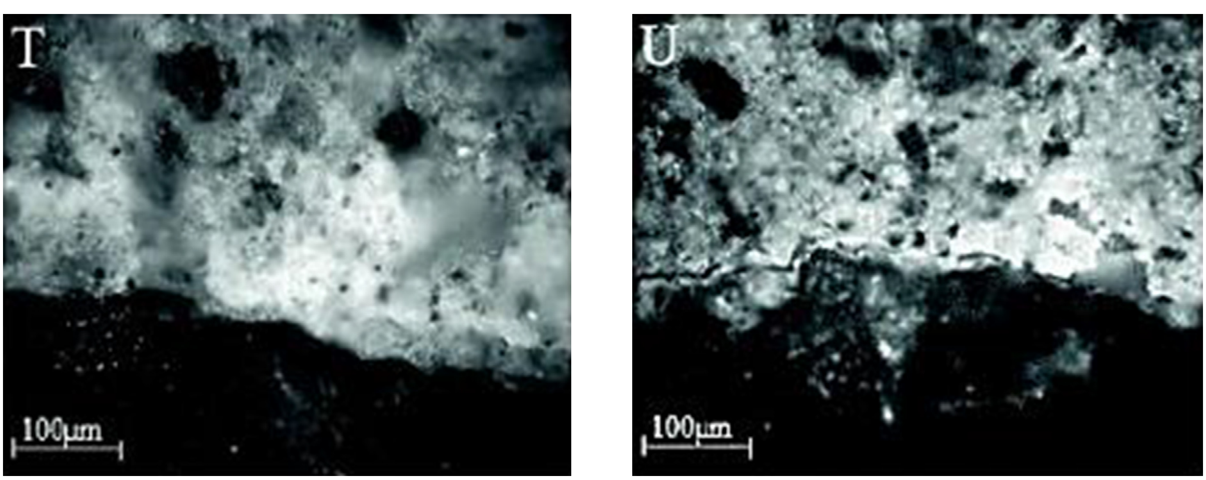
1. The results indicate the useful, economical application of steam curing of concrete for precast structural elements, where one of the objectives is to speed up the construction in addition to the early superior mechanical properties.
2. The application of atmospheric pressure steam curing systems greatly increases the hydration rate to raise the early strength of concrete, achieving the designed strength within 3 days of casting.
3. The application of lower steam curing temperatures from 45 ˚C to 60 ˚C for a longer period (24 h) yields positive results in the early and later ages compared with higher curing temperatures and shorter periods.
4. The application of curing steam temperatures of more than 80 ˚C has a negative effect on the microstructure, the strength of concrete in later ages due to the delayed ettringite formation, and the formation of a porous structure.
5. The most effective steam curing regime is in the temperature range from 50 ˚C to 80 ˚C and the curing period cycle of 24 h to avoid the negative effect of high temperatures and reduce curing costs.
6. Attempting to speed up the transfer of vapor heat to concrete samples by raising the steam curing temperatures or decreasing the period before curing leads to thermal stress and damages the properties of the concrete. Therefore, a sufficient delay period must be provided before steam curing is carried out, which is not less than the initial sitting time of concrete.



a) steam curing temperatures at 45 ºC



a) steam curing temperatures at 60 ºC



a) steam curing temperatures at 75 ºC

Fig. 18. Micro morphology of ITZ at various steam curing temperatures (Shi et al., 2021).

7. The addition of pozzolanic materials plays an important role in reducing the negative effect of steam curing on the strength of concrete in later ages because the pozzolanic reaction occurs late between Ca (OH)2 and amorphous silica, and the ultrapure pozzolanic materials improve the microstructure and reduce permeability.

Future research

The superior mechanical properties and durability of the HSC subjected to steam curing regimes at an early age make it an outstanding candidate for infrastructure systems, especially those that require speed of execution and are exposed to harsh climatic environments.

To apply steam curing of high-strength concrete in practical engineering, the following additional research should be conducted:

(1) Knowing when and how the steam curing regimes can be applied on concrete is critical to avoid damage caused by accelerate the hardening of concrete.
(2) The correlation between steam curing regimes and porosity should be established, and the knowledge of the development of pore volume and pore size distribution of cement paste is needed to clarify the actual mechanisms of steam curing regimes.
(3) The microstructure of cement paste beside concrete under the influence of steam curing regimes must be studied very carefully to explain and demonstrate the variable properties of different steam curing regimes.

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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