Experimental study on the effect of hot climate on the performance of roller-compacted concrete pavement

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Experimental study on the effect of hot climate on the performance of roller-compacted concrete pavement

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Abstract

The aim of this paper is to investigate the effect of hot climate on the performance of roller-compacted concrete which is used for pavement. Mixes were placed in different environments in order to simulate the local climate conditions. Large-scale test has been carried out to assess the mechanical strength development in function of curing mode, temperature treatment and silica fume addition. Compressive strength, splitting tensile strength, shrinkage and capillary absorption of water were evaluated according to the program tests. The main results showed that an increase in temperature (over 40°) affects negatively the physical and mechanical properties due to malformation of hydration products, while cure methods showed a higher efficiency of the improvement in such properties. However, it should be noted that the wet cure method gave the best results as it provides appropriate and effective conditions to the hydration process. Regarding the effect of silica fume addition, even an improvement in the compressive strength was confirmed; however, it has a negative impact on the shrinkage.

Keywords Roller-compacted concrete · Hot climate · Cure conditions · Silica fume · Strength · Shrinkage

Introduction

Roller-compacted concrete used in pavements (RCCP) has the same basic ingredients as conventional concrete. But, as the name suggests, it cannot be placed by the same conventional methods used in the case of ordinary concrete: It is about a mix dry, enough to be compacted by vibrating rollers. Therefore, the fundamental characteristic of RCCP is its dry appearance, which requires the application of compacting forces to consolidate the mix [1–4].

The principal advantages of RCCP consist of easier construction and lower cost in comparison with conventional pavements [5]. The availability of cement and aggregates at acceptable prices in the southern regions of Algeria make the use of such material beneficial, so that approach can minimize the consummation of petroleum-derived by-products. Ramezanianpour et al. [6] reported that using RCCP reduces the cost by 15–30% in comparison with conventional pavement. But, using this kind of concrete in a arid zones climate which is classified by a very hot summer, in which temperatures exceed 56 °C [7], encourages researchers to take a closer look at the impact of climate factors on the properties of concrete and how to develop and make them suitable in these difficult climatic conditions.

Several studies on the behavior of ordinary concrete in a hot climate have been reported in the literature. These studies consist of analyzing the effect of temperature on the mechanical and physical characteristics of concrete. Behrane [8] concluded that the published work on the properties of concrete in a hot climate is incomplete, uncoordinated and sometimes contradictory [9]. The effect of extreme weather conditions on concrete properties has also been studied by Nazir and Saeed [10]. Their study showed that the high temperature slightly increases the concrete compressive strength at early age, but significantly reduces the resistance at a long-term age.

This study aims to investigate the behavior of the RCCP in a hot climate. It is based on the preparation of RCCP mixes with and without additions and placing the samples at different temperatures (15, 30, 45 and 60 °C). The effects of using silica fume are also investigated and reported in the present work.

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Materials and experimental procedures

Materials

The behavior of RCCP made with local materials and placed in different environment climate of M'sila region (hot and wet in the north, hot and dry in the south) was evaluated. The data obtained in this investigation will be helpful in selection concrete materials appropriate for arid or semiarid climate. The basic ingredients used to make the mixes of RCCP are:

- *Portland cement* Portland cement CEM II/A42.5 from Ain Touta Factory in Algeria was used in this work. This cement was chosen because of its wide availability and largely used in the concrete construction sector in Algeria. Its Blain's specific surface area is about 3600 cm^2/g. The chemical and physical properties of cement are, respectively, shown in Tables 1 and 2.
- *Dune Sand (Fine Aggregate)* The dune sand used in this experimental study is clean, siliceous and contains very few fine dust or clay elements (sand equivalent value equal to 71%). The specific gravity and fineness modulus calculated was, respectively, 2.64 and 1.73. The grain size distribution of sand is shown in Fig. 1
- *Crushed Gravel (Coarse Aggregates)* Crushed gravel is obtained by crushing limestone rock from the quarry. Three fractions 3/8, 8/15 and 15/20 mm of coarse aggregates have been used in this experimental study. The specific gravity was 2.54. Since it is a concrete designed for pavement project, the maximum diameter of the aggregate was limited to 20 mm in order to reduce the risk of segregation [11]. Figure 1 shows the granular distribution of the mineral aggregates used for this study.
- *Silica Fume* Micro-silica provided by the company "GRANITEX" in the form of gray powder with fineness greater than 150,000 cm^2/g and an absolute density of 1870 kg/m^3.
- *MEDACURE* It is a product made in GRANITEX factory in Algeria. It comes in the form of a whitish liquid form intended to cover the concrete in order to protect it against desiccation. Its density is 1000 kg/m^3.

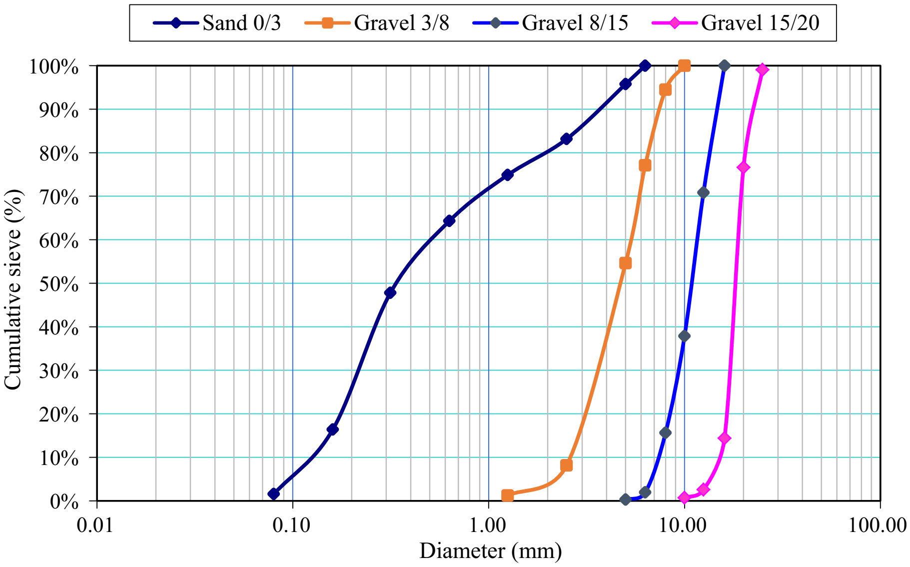
Table 1 Chemical composition of cement

Element	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	Cl^-	PF
%	20.63	4.17	2.52	58.21	1.67	2.99	0.53	0.18	0.020	6.63

Table 2 Physical properties of cement

Standardized consistency	Setting time (min)		Density (g/cm^3)	Fineness (cm^2/g)	Heat of hydration (j/g)	Expansion (mm)
w/c	Start	End				
0.273	165	305	3.1	3600	370	1

Fig. 1 Particle size distribution of aggregates



Procedure and experimental methods

In order to assess the effect of temperature on the performance of the RCCP, necessary mixes of RCCP were prepared under laboratory conditions. The formulation method used is based on geotechnical principles. This method was selected because it is more appropriate for the pavement project [2, 5]. Granularity is chosen to obtain a combined particle size distribution between the limits recommended by the US Army of Engineers as reported in the work of Nanni and Meamarian [12]. This combined distribution is illustrated in Fig. 2. The cement and water contents were chosen using the soil mechanics procedure according to ASTM D1557 [13]. This method is based on the relationship between dry density and water content (Proctor test) [13].

Standard molds of concrete specimens were prepared in accordance with ASTM C470 [14]. Each mold thoroughly cleaned, dried and then lubricated before the concrete was poured. Cubic (100 × 100 × 100 mm), cylindrical (100 × 200 mm) and prismatic (70 × 70 × 280 mm) test specimens were used, respectively, for the measurement of compressive strength and water absorption, splitting tensile strength and shrinkage.

The constituents of RCCP were mixed in an electric rotating drum concrete mixer. The ingredients were initially mixed in the dry state, and then, water was added. The molds were filled in several layers (depending on shape and size) and compacted until RCCP consolidation.

The compaction of RCCP cylinder specimens was performed using a vibrating hammer according to ASTM C1435/C1435M [15]. For molding of prismatic and cube specimens, the same procedure has been used with placing the appropriate base [16]. After casting, the specimens were then air-dried for 24 h prior to demolding, and then, their initial weights were recorded and cured in correspondent medium.

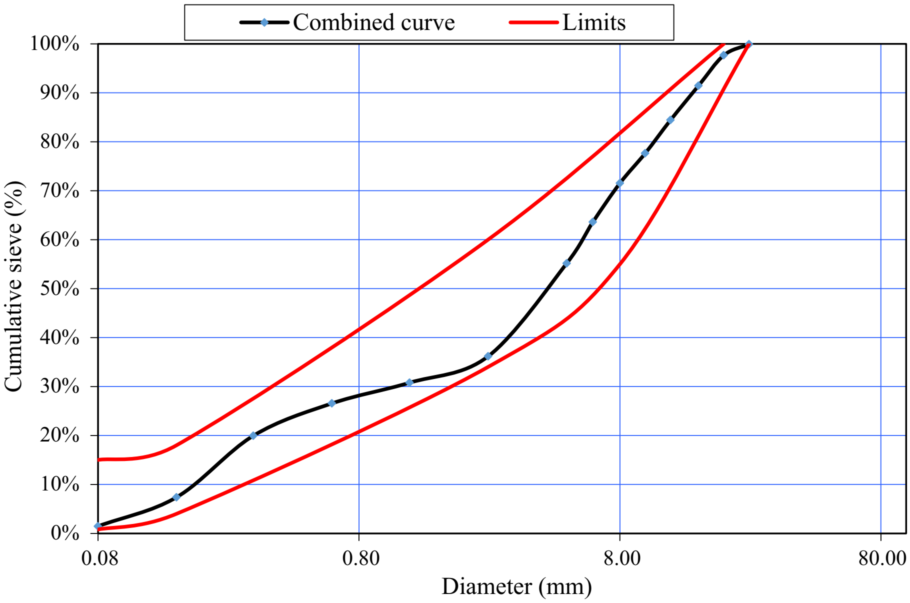
The compressive and splitting tensile strengths were evaluated at ages 3, 7, 14, 28 and 60 days according to ASTM C39 [17] and ASTM C496 [18]. The drying shrinkage readings were taken at different ages according to ASTM C157 [19]. Furthermore, the arithmetic average of six values was taken for all tests. Capillary absorption of water tests was performed on specimens after 28 days of curing according to ASTM C1585 [20]. The samples used in this work are cubic specimens (100 × 100 × 100 mm) dried up to a constant mass in an oven at 105 °C. They are then immersed in a 2-mm-thick water plate for 72 h. Measurements are taken at intervals: 120, 240, 360, 480, 600, 840, 1560, 2520 and 4320 min.

Curing conditions

A climatic chamber equipped with water tank allowing controls both temperature and humidity was used in this investigation. RCCP specimens were prepared to be studied according to the test programs. The first part of the study involves placing the RCCP specimens inside the climatic chamber at different temperatures (15, 30, 45 and 60 °C; RH 50). These specimens are, respectively, noted as P15, P30, P45 and P60.

The second part of the program consists of applying three methods of traditional and technical cure. These methods consist of placing the specimens directly under water (PW), under wet burlap (PB) and the application of a cure product, which is the MEDACURE (PM), at a medium of (45 °C and 50 RH) to simulate the Saharan environment during the day. These cure regimes were applied after 24 h (after

Fig. 2 Position of combined granulometric curves according to Marchand et al. [2]



demolding) for 13 days and then removed. After 14 days, the specimens continue their maturing in the climatic chamber at (45 °C and 50 RH). These are illustrated below:

- PW: total immersion in water at a temperature of 45 °C for 13 days, then specimens are placed in conditions of (45 °C and RH 50) until the test date.
- PB: covered with moist burlap and hardened for 13 days at the medium of (45 °C and RH 50), then the burlap is removed and kept under the same conditions.
- PM: applying the MEDACURE and cured for 13 days at the medium of (45 °C and RH 50%), then the curing compound is removed and stored under the same conditions.

The third part aims to study the effects of incorporating silica fume in RCCP as partial replacement of cement with different percentages; 3, 6 and 9%. The specimens prepared for this purpose were placed at (45 °C and 50 RH) and named as PSF3, PSF6 and PSF9. In summary, the experimental procedure followed is given in Table 3.

Results and discussions

Effect of temperature on the RCCP

Compressive and splitting strengths

Generally, the material laws for hardening were mainly based on the age of concrete; however, in reality the climate temperature influences its mechanical properties. In this part of the study, the effect of temperature on the mechanical properties was investigated to obtain experimental scientific results in order to minimize the negative effects when making RCCP in hot regions.

Compressive and splitting strengths were determined at 3, 7, 14, 28 and 60 days after placing in different temperatures as given in program tests. The results obtained are shown in Figs. 3 and 4 for compressive and splitting tensile strengths, respectively. It can be noted that the final values decrease with the increase in temperature. For example, the 60-day compressive strength decreased by 13% and 34% when the temperature is changed, respectively, from 15° to 45° and 60°, whereas the splitting tensile strength is decreased by 11 and 21%, for the same interval of temperature. However, it should be important to note that strength evolution kinematics is increased with the increase in temperature. For example, 84% of final value of compressive strength is achieved after 3 days of curing at temperature of 60°, while it reached only 72% when specimens were cured at temperature of 15° which is advantageous for pavement projects. These obtained results are in agreement with other studies carried out on ordinary concrete (Shoukry et al. [21], Lawson et al. [22], Phan and Carino [23])

The decrease in strength in high temperature can be explained by the reduction in the amount of water required for hydration of cement in the mix. Several researchers [24, 25] used this argument to justify the loss of strength of cement-based materials in hot climate zones. They mentioned that the high rate of evaporation in hot areas reduced the amount of water in the mix and consequently affected the hydration processes. In addition to this, evaporation of water can create dispersed and poor hydration products in the mix.

Gallucci et al. [26] and Wang et al. [27] have reported that the decrease in strength in higher temperatures was due to the denser, heterogeneous and coarser distribution of hydrates, more precisely the CSH responsible for the development of the resistance. This effect can beget hydrated phases around the anhydrous cement grains preventing the formation of CSH based on the C_3S hydration reaction and the nucleation procedure of CSH on the surface of C_3S.

Zacak et al. [28] have stated that when the temperature is higher, the CSH layer is denser. This is why the C_3S hydration rate is rather low at high temperatures. Escalante-Garcia [29], in his work on 5 types of cements

Table 3 Mix concrete proportions

Mix	Silica fume (%)	Curing temperature (°C)	Constituents (kg/m^3)				
			Cement	Sand	Gravel 3/8	Gravel 8/15	Gravel 15/20
P15	–	15	300	821	588	392	196
P30	–	30	300				
P45	–	45	300				
P60	–	60	300				
PW	–	45	300				
PB	–	45	300				
PM	–	45	300				
PSF3	3	45	291				
PSF6	6	45	282				
PSF9	9	45	273				

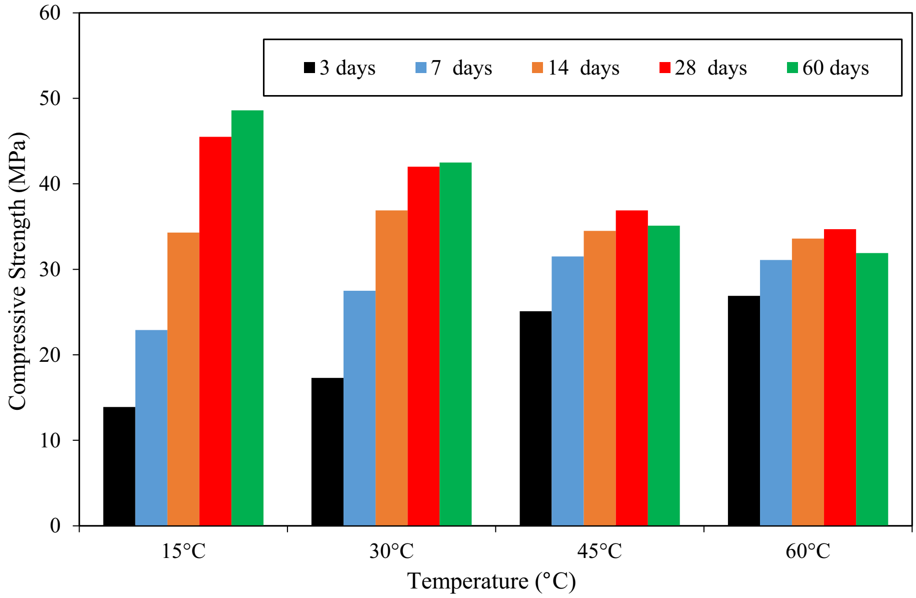


Fig. 3 Effect of curing temperature on compressive strength

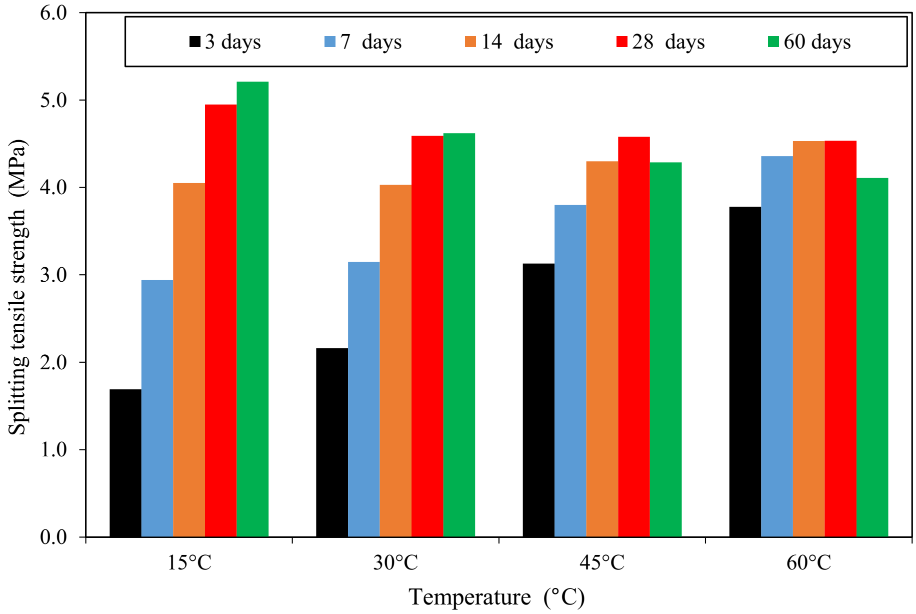


Fig. 4 Effect of curing temperature on splitting tensile strength

with a maturation at different temperatures ranging from 10 °C up to 60 °C, concluded that the degree of hydration and the amount of non-evaporable water accelerate or increase with increasing temperature, but at older ages they reverse, which means that both factors become lower at higher maturation temperatures.

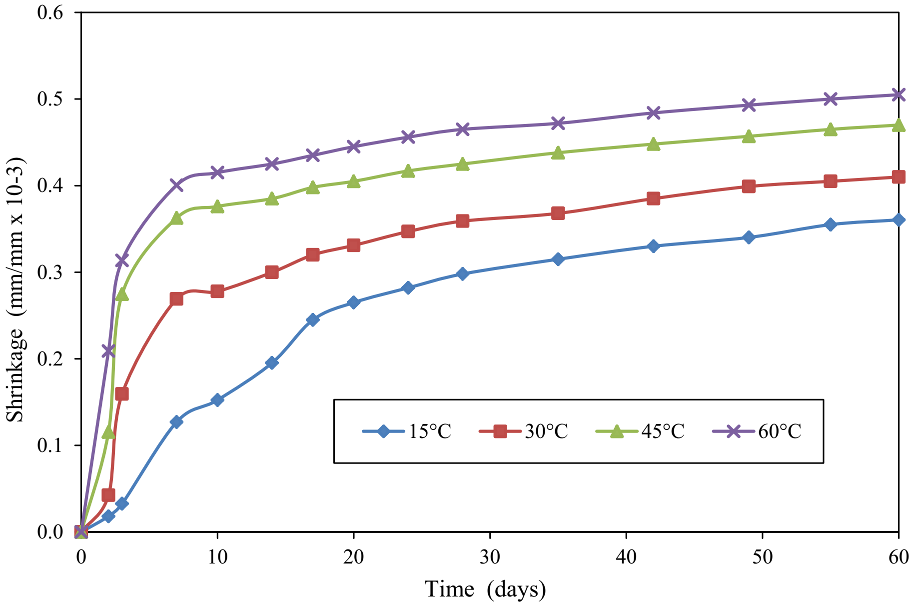
For the temperature range studied in this work, the resistance and temperature data can be adapted to linear relationships. The loss of compressive strength was 0.38 MPa per 1 °C increase in temperature, while the loss of splitting tensile strength was 0.024 MPa per each 1 °C increase in temperature.

Shrinkage

Volume changes are strongly related to moisture content [30]. The drying shrinkage starts at early age due to the evaporation of water. The shrinkage of concrete is amplified in the case of large concrete-based surfaces such as pavements, with a high surface/thickness ratio, where water loss can be significant, especially at hot weather.

Figure 5 shows the variation of shrinkage for RCCP mixes in 60 days. It clearly can be seen that the drying shrinkage deformation increases with the increase in temperature. This effect is more important at early age of specimens due to the

Fig. 5 Evolution of the shrinkage of RCCP in time



microscopic cracks created by the evaporation of water, as shown in Fig. 6. These results are in agreement with other studies carried out on ordinary concrete [31–34].

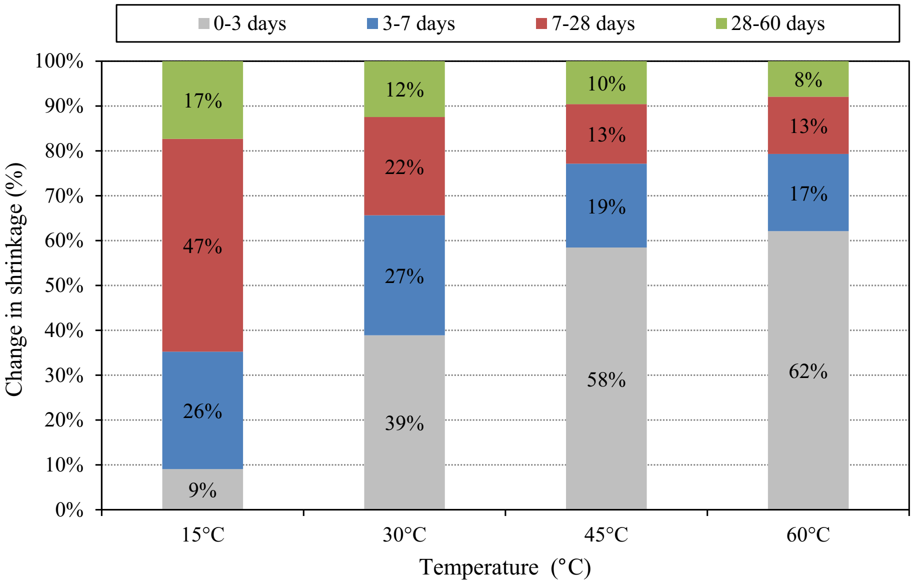
The drying shrinkage increased by 13.7, 14.6 and 7.4% for the temperature ranges 15–30, 30–45 and 45–60 °C, respectively. So these shrinkage variations are not proportional to the temperature. This difference can be explained by the hydration mechanism and the potential of cement reactions and their relationship to temperature [35, 36].

These findings are also affirmed by Lura et al. [31] when they worked on different types of cements with the introduction of silica fume and with a water/binder ratio about of. They found that high temperatures cause a faster development of shrinkage without creating more important deformations. Yang et al. [37], in their work, treated mixes at different temperatures (20, 35, 50 and 60 °C) with different w/b ratios. They have concluded that high temperatures accelerate the speed of hydration of cement, which generated additional evaporation, reduced the internal relative humidity and consequently amplified the deformation of the concrete. Chu et al. [32] had observed the same phenomenon for concrete prepared at different water/binder ratios.

Absorption of water by capillarity

The evolution of capillary absorption of water for RCCP mixes as a function of curing temperatures is shown in

Fig. 6 Shrinkage variations



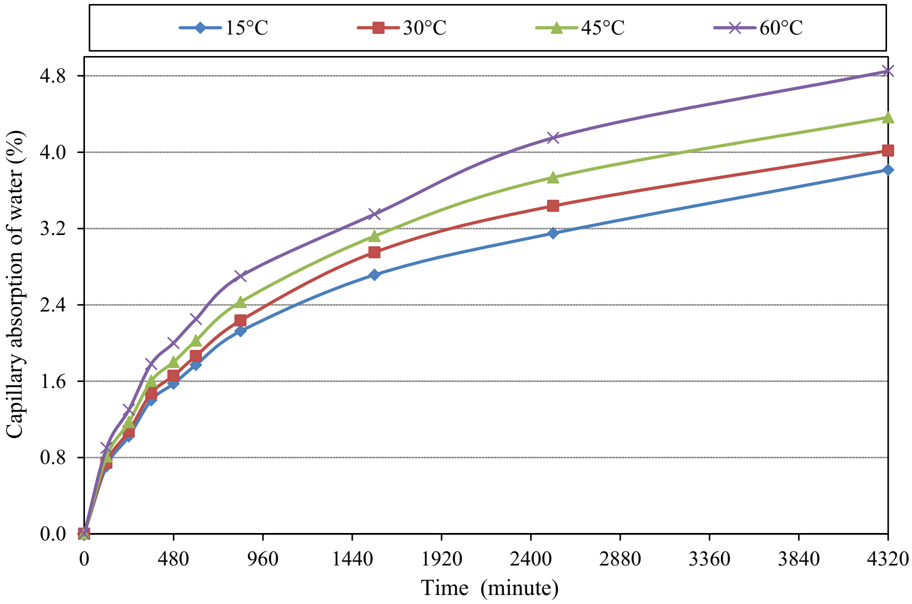


Fig. 7 Effect of curing temperature on capillary absorption of water

Fig. 7. It can be seen that the capillary water absorption evolved in a similar way for all adopted temperatures.

Like the two previous parameters, the absorption is very sensitive to the conditions of maturation where the elevation of the temperature increases the capillary absorption. In their study, Goto and Roy [38] have reported that the permeability of pastes hardened at 60 °C is higher than that hardened at 27 °C. They have stated that the volume of pores with radius larger than 750 Å was more important for specimens cured at 60 °C. Joshaghani et al. [39] indicated that the increase in temperature causes cracks in the microstructure of the cementitious material, which increases the absorption. This is due to the heterogeneous distribution of the CSH gel during the hydration of the cement. Pinto et al. [40] agree that at high temperatures (70 °C), the evaporation of water is higher which created microscopic cracks in the concrete, and thus contributed to the increase in absorption rate.

Effect of curing methods

Compressive strength

Figure 8 illustrates the effect of curing method on the 60-d compressive strength for RCCP. For this part of the study, the specimens were cured at constant temperature (45 °C). This figure shows that the compressive strength was affected

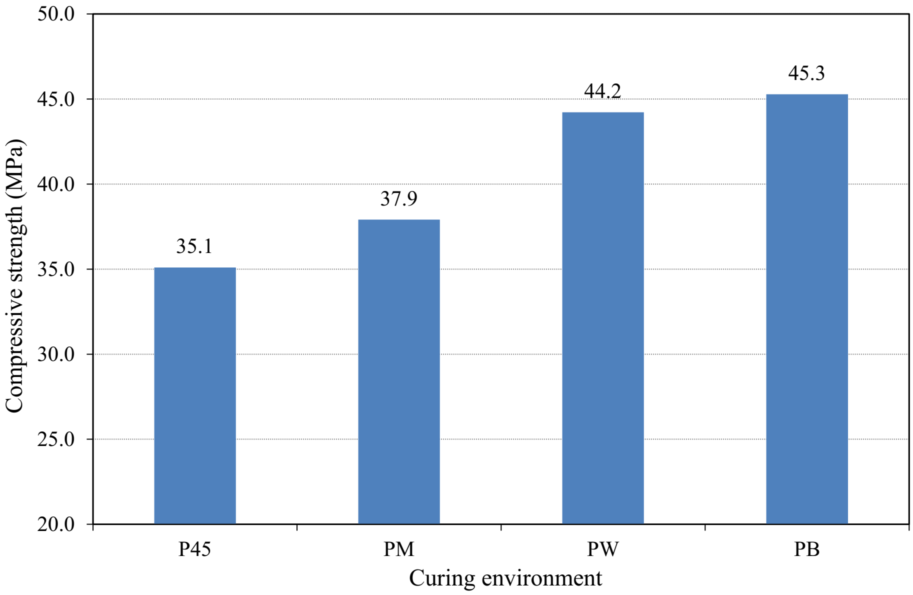


Fig. 8 Effect of curing method on compressive strength of RCCP

by the mode of curing. In comparison with the control mix (P45), the final strength is improved by 8, 26 and 29% for mixes PM, PW and PB, respectively. The increase in strength can be explained by the fact that wet cure methods reduce the desiccation of concrete and conserve enough water to ensure the hydration process.

Water immersion, liquid curing compounds and coating with wet geotextile tissues were evaluated by Wasserman and Bentur [41]. They indicated that the effect of the different cures on penetration characteristics is much greater than that observed in compressive strength. They also reported that the cure with a wet tissue was more effective than the standard water cure in regard to strength. Bushlaibi and Alshamsi [42] exposed a high strength concrete to different cure methods where they found a significant influence of the cure methods on compressive strength with a preference inside a climatic chamber rather than outside it. Al-Gahtani [43] conducted a study on different cure modes for concrete: under burlap, immersion in water and the application of acrylic film. He found that the compressive strength given by mix cured under burlap was the best. Nevertheless, all these authors have found that the immersion under water of the concrete specimens does not record the best strength; this is due to the internal hydrostatic pressure in the pores.

In general, the data obtained in this study indicated the utility of the selected cure methods for enhancing the performance of RCCP.

Fig. 9 Evolution of the shrinkage for different curing environments

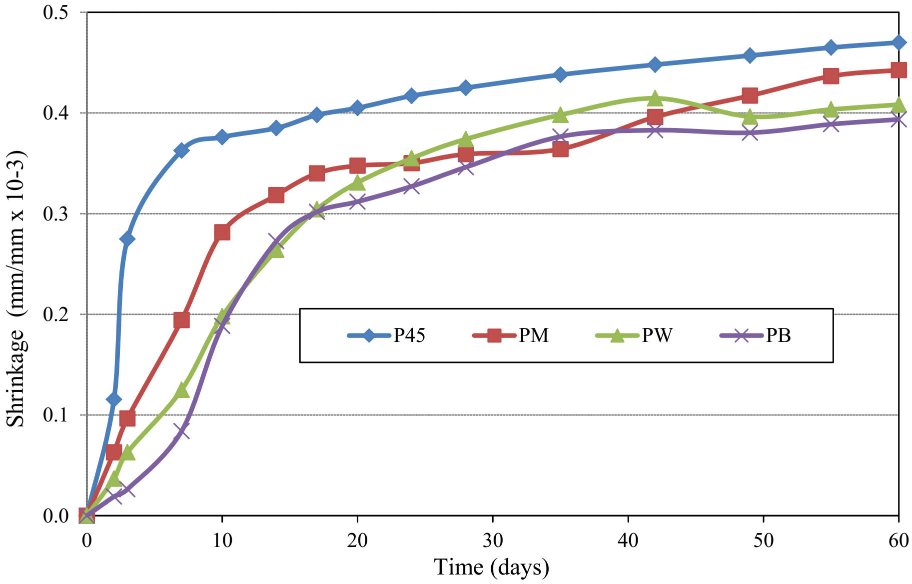
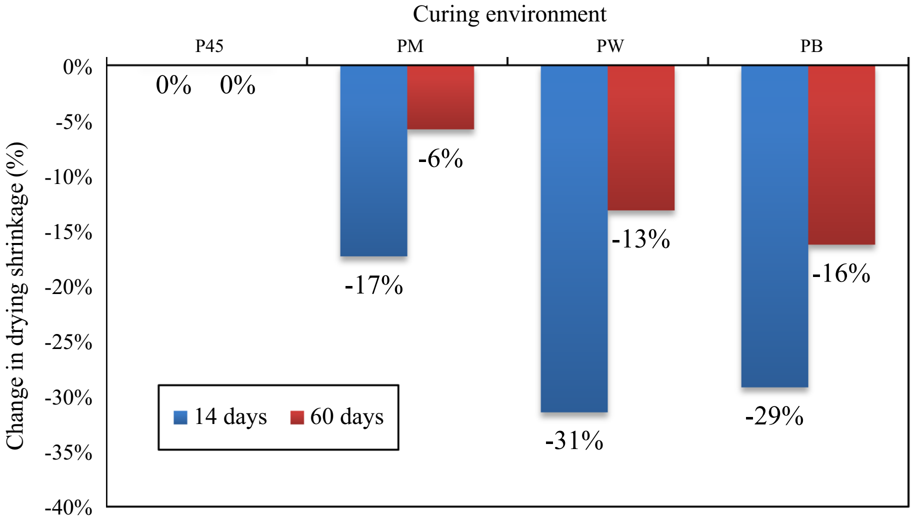


Fig. 10 Variations of the shrinkage for curing environment



Shrinkage

Figures 9 and 10 show the effect of curing methods on the shrinkage of hardened RCCP at a temperature of 45 °C. This figure shows that shrinkage increases with the age for all RCCP mixes, regardless of the mode of cure adopted.

It is obvious that the effect of the different cure methods was positive, because they reduce the shrinkage, especially in the first 2 weeks of application, where there is a decrease of 17, 31 and 29% for PM, PW and PB, respectively, and these percentages were calculated in comparison with the mix P45.

It is also interesting to note that after the first 2 weeks, the mix PW has a lower shrinkage than the PM and the PB, while at 60 days the minimum shrinkage value is attributed to the PB.

However, there was no significant difference in the shrinkage of RCCP hardened in water and RCCP hardened by covering it with moist burlap. Here, we can emphasize that the shrinkage results do not conflict with those of the compressive strength from this study as moist cure methods retain more moisture and thus give better long-term development of compressive strength and also lower permeability than any cure mode.

Generally, it can be noted that all the treatment methods were useful for improving the behavior of RCCP mixes with regard to the shrinkage by reducing the evaporation of the water and consequently the tensile stresses between the walls of the capillary pores [30]. These results agree with other reports on different types of concrete, including the study of Maslehuddin et al. [44] who found the superiority of wet burlap to improve shrinkage compared to other methods. McCarter and Ben-Saleh [45] reveal that plastic sheeting reduces total water loss by an order of 4 during the first 6 h compared to uncovered specimens, and because of the fibrous nature of the burlap, it is impervious to airflow and it reduces shrinkage like a plastic sheeting. On the other hand, Nabil et al. [46] state that the cure with immersion under water can remove fine particles from cement, and in another study [47], they found that, using a 6 factor test design, the curing product hides the effect of the other methods and interacts only with the plastic sheet in reducing the cracks produced by the shrinkage. The plastic sheet reduces evaporation and does not interact with any other curing method thanks to its moisture retention and concrete insulation.

Effect of silica fume

Compressive strength

The incorporation of silica fume in concrete has several effects, whose strong pozzolanic property is only one. It accelerates the reactions of the clinker phases. The fine particles fill spaces between clinker grains, thereby producing a denser paste. It also reinforces the interfacial transition zone between cement paste and aggregate; this increases the strength and lowers the permeability [48].

Figure 11 shows the effect of silica fume on the compressive strength of RCCP cured at 45 °C with time. This figure shows that the incorporation of silica fume increases the compressive strength of the RCCP. The 3% replacement of cement by silica fume had no significant effect on compressive strength (an increase of 2.1%), while the addition of 6% and 9% silica fume significantly increased the compressive strength of the RCCP by 11.9% and 24%, respectively. These observations indicate that the temperature can significantly

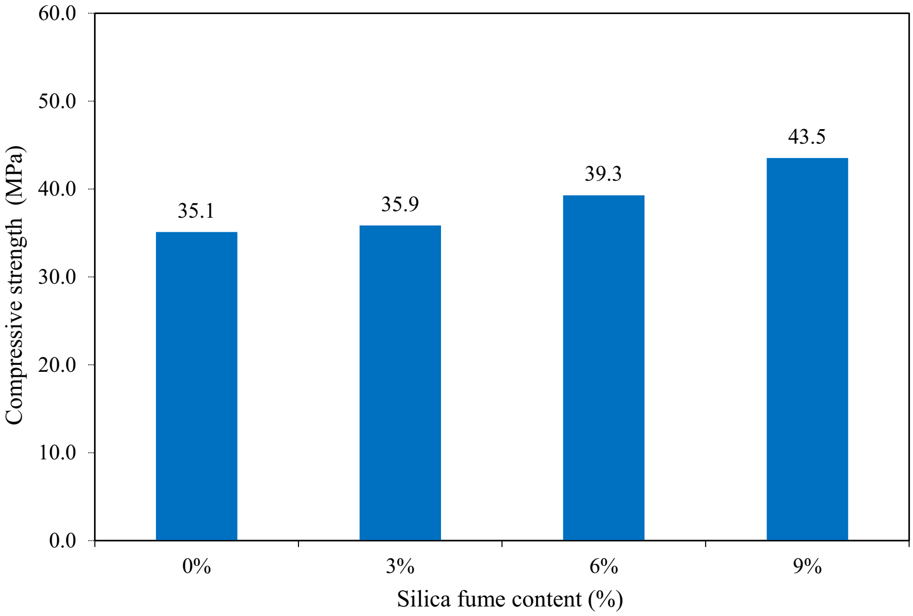


Fig. 11 Effect of silica fume content on compressive strength

decrease the compressive strength of the RCCP. However, this negative effect can be reduced by adding silica fume. Similar results have been reported by numerous studies on different types of concrete such as the Bhanja and Sengupta study [49] and Mohamed [50] study.

The silica fume is a pozzolanic supplementary cementitious material; it accelerates the hydration reaction of cementitious minerals and fills the space between the voids of the cement grains which makes the cementitious paste denser. The silica fume makes the transition phase between the cement paste and the aggregates more compact, which implies an increase in mechanical strength [48]. In this zone surrounding the aggregates, the w/c ratio is higher, which favors the dissolution of the cementitious components; thus, the calcium hydroxide and the hydrated calcium silicate gel form a film approximately 1 µm thick [30]. Hu and Stroeven [51] found that during dissolution, the ions Ca^{+2}, Al^{+3} and SO_2^{-4} with very high mobility cause the precipitation of portlandite and ettringite, while the very low-mobility silicates ions attempt to form hydration products near their source of dissolution, hence the need to increase the amount of silicate ions in the transition zone. Nevertheless, with the introduction of silica fume, Xuan et al. [52] found that the tensile strength is high with increasing silica fume rate, but beyond 9% the improvement becomes stable.

Shrinkage

Figure 12 shows the effect of silica fume on shrinkage of RCCP cured at 45 °C with time. This figure shows that the deformation increases with age for all mixes independently of the silica fume content. It can also be noted that the increase in silica fume content in the mix increases the shrinkage.

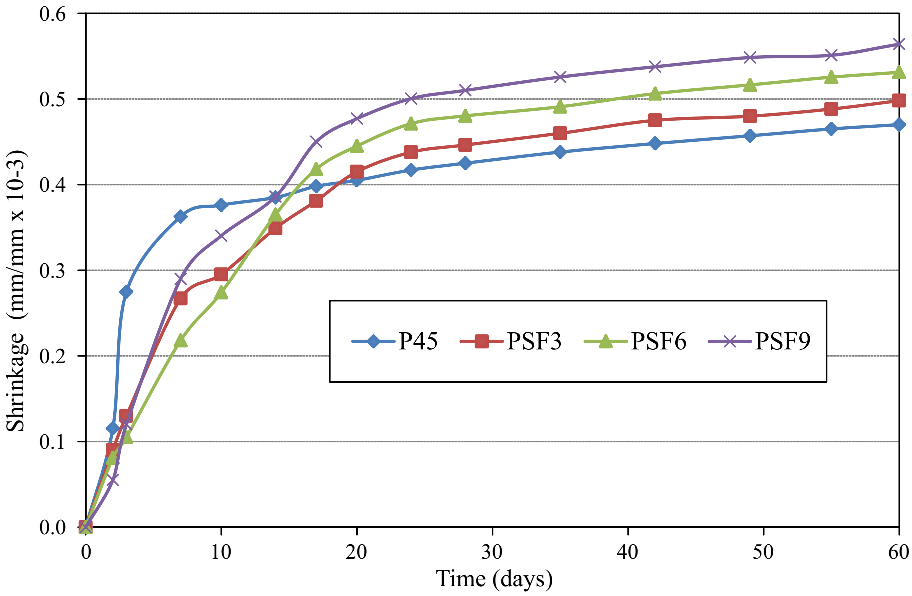
This same remark was noted by Al-Amoudi et al. [53] on slabs of 3×3 m^2 and 5×5 m^2 with a concrete with 8% of silica fume, where they noticed a low rate of bleed water, which improves the evaporation inside the layers concrete especially in hot weather. In another context, a denser matrix will be provided with smaller capillary pores; thus, more water enclosed in these pores leads to the reduction in bleed water as indicated by Ghassemzadeh et al. [54]. Hooton [55] reported that shrinkage of low silica fume concrete did not increase significantly, while concrete with a higher percentage of silica fume exhibited a significant increase in shrinkage.

Conclusion

The effect of hot climate on the behavior of RCCP is experimentally investigated in this paper. The experimental results showed that physical as well as mechanical properties of RCCP are affected by hot climate of arid zones. Specifically:

- When temperature achieved to high levels, the rate of development of strength is affected; however, it should be important to note that the temperature accelerates the kinematic of development of strength at early ages that is advantageous for RCCP projects.
- At hot weather, the evaporation of water increases which may affect the hydration, create microscopic cracks and decrease the mechanical properties of concrete.
- Both strength and shrinkage of RCCP are highly affected by the cure conditions. Therefore, it is found that these

Fig. 12 Effect of silica fumes on shrinkage



parameters are improved by the different curing methods adopted in this study. However, it should be noted that curing under wet burlap is more effective than other methods.

- The partial replacement of cement by silica fumes helps to enhance strength due to its high pozzolanic reactivity and extreme fineness. But, it is recommended to limit its use at 9% due its direct effect on shrinkage.

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