Scientific Research and Essays Vol. 6(12), pp. 2504-2511, 18 June, 2011
Available online at http://www.academicjournals.org/SRE
DOI: 10.5897/SRE11.269
ISSN 1992-2248 ©2011 Academic Journals

Full Length Research Paper

The effect of curing temperature and relative humidity on the strength development of Portland cement mortar

Hayri UN[1] and Bulent BARADAN[2]

[1]Department of Civil Engineering, Pamukkale University, Denizli, Turkey.
[2]Department of Civil Engineering, Dokuz Eylul University, Izmir, Turkey.

Accepted 6 May, 2011

The aim of this study is to determine the effect of humidity on development of mechanical properties of Portland cement mortars under different curing regimes. The curing conditions were selected in order to simulate the average seasonal climatic conditions in various regions of Turkey. Conventional maturity formulas for Portland cement usually neglects the effect of humidity. However, especially under low relative humidity conditions the test data obtained in this paper reveals that; this assumption is no longer valid. Test results also include the comparative data on relation between compressive and flexural strength, compressive strengths of 50 mm cubic and 40×40×160 mm prismatic mortars.

Key words: Relative humidity effect, temperature effect, maturity, mortar.

INTRODUCTION

Although extensive research about complex hydration process of Portland cement has been carried out, there remain many aspects not yet fully understood and questions to be answered. Many variables affect the hydration of Portland cement, such as, fineness, chemical composition of cement, and temperature and relative humidity of mixing and curing conditions, etc. (Garcia and Sharp, 1998)

The strength and microstructure of concrete and mortar are known to be affected by drying process. Removal of significant amounts of water from cement paste before maturation, in inadequate curing conditions results in inferior properties and poor performance. Furthermore, the mechanical properties of a cement-based material at any age are generally a function of its moisture content. Drying has also a great influence on the degree of shrinkage and stress state of the system (Kanna et al., 1998; Ho et al., 1989).

Drying shrinkage influences the microstructure in many levels and, it affects the mechanical properties in two basic ways. In one respect, it tends to increase strength by increasing surface energy and increasing bonding between particles of calcium silicate hydrate (C-S-H). In another respect, since it is a quasi-brittle material, the strength is reduced by microcrack formation. The extence of cracking depends on the rate, and severity of drying, and the sample geometry (Kanna et al., 1998; Ho et al., 1989).

The established wisdom is that concrete cast and cured at low temperatures develops strength at a significantly slower rate than similar concrete placed at room temperature. For example, Price (1951) and Klieger (1958) separately determined that concrete mixed and placed at 4°C had a 28-day compressive strength 22% lower than concrete cast and cured continuously cured at 21°C. Gardner et al. (1988) and Ho et al. (1989) indicated that the expected slow strength development at low temperatures was not realized for cold cast and cured concretes.

Moisture gradients created by exposing concrete to drying atmosphere can cause gradients of hydration and porosity. The extend and severity of these gradients will depend on a number of factors such as; the ambient relative humidity, the temperature, the wind speed, the age at exposure, the depth from the exposed surface and duration of the exposure. If the relative humidity of the surrounding air is low enough, the hydration of the cement at the exposed surface of an element may cease (Cebeci, 1987). However, in the interior of the concrete,

*Corresponding author. E-mail: hun@pau.edu.tr. Tel: +90 258-295 3355. Fax: +90 258-212 5548.

Table 1. Composition and properties of cement used in this study.

Chemical composition of clinker, percent	
SiO_2	19.69
Al_2O_3	5.19
Fe_2O_3	3.56
CaO	63.62
MgO	0.92
SO_3	2.4
Minerogical composition of clinker, percent	
C_3S	63.60
C_2S	9.35
C_3A	6.62
C_4AF	10.99
Loss on ignition, percent	1.30
Blaine specific surface (m^2/kg)	350
Vicat setting time (hour:min.)	
İnitial	1:45
Final	2:45
Compressive strength, MPa	
1 day	17.0
2 days	25.0
3 days	33.0
7 days	41.0
28 days	50.0

the cement will continue to hydrate while adequate pore water is still available. The pore water will be partly consumed in the hydration process and some will be lost through the drying surface. It has been suggested by Powers (1947) that the hydration of cement virtually ceases when relative water vapour pressure in capillaries drops below about 0.8. Spears (1983) claims that continued curing below 80% relative humidity does not lead to the increase in cement hydration which is necessary for further improvement of concrete quality. In practice, site concrete subjected to daily humidity cycles superimposed upon seasonal variations, and active curing may stop before cement has fully hydrated. Data in the literature concerning the effect of relative humidity of curing and microstructure properties of either cement or its products are scarce (Patel et al., 1988).

Established maturity formulas which are a function of time interval and temperature do not incorporate the effect of humidity on the strength development of Portland cement mortars. However, it is apparent that the effect of humidity may considerably change the hydration process even under same temperature.

From durability point of view, curing is essential to improve the quality of cover of concrete, blocking the ingress of aggressive substance into the concrete structure. Chloride ion induced corrosion of reinforcing steel is an extensive problem (Neville, 1999; Baradan et al., 2002).

MATERIALS AND METHODS

The experimental program was planned in order to assess the strength development of Portland cement mortars cured at different temperature and relative humidity conditions. The seasonal climatic conditions simulate various regions of Turkey. In this program specimen size and shape effect and pH degree of curing media has been also studied.

Materials

In this research, a commercially available normal Portland cement (CEM I 42.5N) produced by Cimentas in Izmir, Turkey was used. The chemical composition and physical properties of cement used in all experiment are given in Table 1 according to data provided by the cement manufacturer.

The aggregate used in experiments was natural river sand with 4 mm maximum size. The properties of sand were in conformity with Turkish Standard TS 706 EN 12620 (Turkish Standard, 2009).

Mixtures and specimen preparation

The mortar mixtures were prepared with a water/cement (W/C) ratio of 0.50 and a sand/cement ratio of 3. Test specimens (50 mm cubes and 40×40×160 mm prisms) were prepared at laboratory conditions (20±2°C and 60±5% relative humidity) according to TS EN 196-1 (Turkish Standart, 2009). For each batch, 3 prismatic and 3 cubic specimens were prepared in approximately 30 min. The specimens were immediately transferred into the temperature-humidity controlled curing cabinet after casting. Specimens were demolded 24±2 h later and then were replaced into the cabinet again. All specimens were kept in the curing cabinet until the testing periods. The control specimens were kept in tap water (20±2°C) under laboratory conditions for 24±2 h and another series of control specimens stored in lime-saturated water at 20±2°C in order to determine the effect of pH degree of curing water. The pH of the city water was 7.0 to 8.0, while the pH degree of lime saturated water was measured as 12.0 to 13.0.

Curing conditions

The effect of curing conditions on the mechanical properties of mortars has been investigated. These six curing conditions presented in Table 2 simulate typical critical climatic conditions of different regions of Turkey. For hot and low humidity conditions, 32°C, 35% relative humidity (RH), for cold and high humidity conditions 4°C, 75% RH, for moderate conditions 15°C at 55% RH and 75% RH were chosen. Also for standard conditions the control specimens were continuously stored at 20°C in water with two different pH levels; tap water (20°C-in TW), and Lime Saturated Water (20°C-in LSW) separately. The pH value of tap water and lime saturated water were approximately 7.0 to 8.0 and 12.0 to 13.0 respectively. The pH degree of curing water was measured after 24 h then the specimens were placed into tap water and lime saturated water separately. After approximately 12 h, it was found that the pH value was approximately same and was equal to ≈12.0 to 13.0 in TW and LSW. These results did not change within testing period.

The temperature and relative humidity were monitored by using a digital thermometer and humidity meter. The deviation of temperature and humidity was ±2°C and ±5% during curing period of specimens, respectively.

Testing

Compressive, flexural and compressive strength after flexure test were recorded for 2, 7, 14, 21 and 28 days for each curing conditions. Three cubes were tested in compression according to ASTM C109 (ASTM International, 2002) and three prisms were tested in flexure then their broken parts were tested in compression according to TS EN 196-3. The averages of three test results were taken and the coefficient of variation of the test data was in the range from 0.33 to 4.90%. The test data is presented in Table 2.

RESULTS AND DISCUSSION

The compressive and flexural strength development of mortars may generally expressed by the following natural logarithmic equation:

$$S = ALn(t) + B$$

Where:
S: Strength, t: time (day), A,B: constants.

The coefficient of correlation for logarithmic expressions varied between 0.99 and 0.58. The parameters of the equations are presented in Table 3.

Compressive strength of mortars

For 50 mm cubic specimens, the compressive strengths developed under different temperature-humidity regimes are presented in Figure 1. As it can be observed from Figure 1, two-day strengths at various curing conditions confirm the well-known effect of temperature on strength of cementious material under high relative humidity. However, after 2 days the negative effect of continuous low humidity curing can be clearly seen. After 2 days, due to the excessive loss of water from the drying surface under low humidity, there will not be enough water for continuation of hydration process. Due to this fact, under 15°C, 55% RH strength increased till 7 days and at 32°C, 35% RH strength increased up to 2 days. Beyond those periods even a small reduction in strength was observed under both of these conditions. Beyond 75% and above relative humidity existence, the strength development continued up to 28 days, implying that specimens sustained sufficient internal moisture. Compressive strength of the cold specimens (4°C, 75% RH) reached and slightly exceeded that of the warm ones (32°C, 35% RH) after about 10 days of curing.

Under continuous low relative humidity curing, due to the lack of sufficient capillary water for continuation of hydration process, the strength development has been ceased. At low temperature curing (4°C, 75% RH) there was sufficient water for hydration however the reaction rate decreased with decreasing of temperature as seen in all chemical reactions.

According to Spears (1983), once the internal relative humidity drops below 80%, the rate of hydration is low and negligible below 30% relative humidity. Hence hydration and strength development are expected to stop earlier in the warm and dry environment than in the cold and humid conditions. Test results presented in Figure 1 confirm that the greater early strength acquired at 32°C was high enough to keep the mortar stronger than the ones kept at 15°C.

The similar behavior can be observed on the compressive strength of prisms after flexural test in Figure 2.

Effect of specimen size and shape

Theoretically, under same conditions, the measured strength of specimens with a larger cross-sectional area is to be expected smaller than the strength of small specimens up to a limit (wall-effect). On the other hand, the effect of curing regimes on measured strength depends on the specimen size, and when the concrete is allowed to dry, measured strength is adversely affected particularly when small specimens are involved (Soroka and Baum, 1994). Thus in evaluating the effect of

Table 2. Compressive strength, flexural strength and compressive strength after flexural test of mortars cured at different temperature and relative humidity conditions.

Specimen	Curing condition	Age (days)									
		2		7		14		21		28	
		S* (MPa)	CV* (%)	S* (MPa)	CV* (%)	S* (MPa)	CV* (%)	S* (MPa)	CV* (%)	S* (MPa)	CV* (%)
Compressive strength of 50 mm cubic specimens	4°C, 75%RH	17.01	2.94	31.63	2.30	34.19	1.06	33.76	2.25	33.99	4.60
	15°C, 55%RH	19.16	2.30	28.15	0.64	26.96	0.30	25.23	3.91	27.86	2.80
	15°C, 75%RH	24.01	2.87	37.41	0.38	41.01	1.02	52.96	2.30	57.67	1.60
	32°C, 35%RH	25.91	3.01	31.88	1.70	31.23	0.58	31.65	1.33	30.93	4.05
	20°C in TW	20.99	2.13	37.41	1.58	43.44	0.51	46.73	0.91	52.89	2.73
	20°C in LSW	24.00	4.10	38.29	2.15	45.04	1.92	50.00	2.30	58.39	1.64
Flexural strength of prisms	4°C, 75%RH	3.72	0.73	5.48	4.59	5.14	4.76	5.67	0.83	5.86	4.80
	15°C, 55%RH	3.48	3.71	4.83	3.88	4.86	3.10	4.52	2.59	4.21	3.26
	15°C, 75%RH	4.64	0.51	5.92	1.99	6.59	1.78	8.20	3.48	7.60	4.16
	32°C, 35%RH	4.78	4.90	5.64	1.73	6.12	0.38	6.36	3.78	5.95	0.79
	20°C in TW	5.41	4.10	7.79	3.13	8.14	0.33	8.47	3.15	8.75	3.57
	20°C in LSW	5.75	4.32	7.77	0.35	8.36	4.36	8.53	3.34	8.75	3.57
Compressive strength of prisms after flexural test	4°C, 75%RH	15.55	3.09	27.4	4.47	27.39	4.65	29.06	4.22	29.80	4.33
	15°C, 55%RH	16.55	4.35	23.91	4.33	24.25	4.16	21.95	4.42	23.09	4.79
	15°C, 75%RH	19.06	2.57	28.53	2.50	35.46	3.25	44.47	2.45	42.45	4.30
	32°C, 35%RH	22.38	4.90	25.38	2.39	26.76	4.13	27.44	2.76	25.44	4.67
	20°C in TW	19.38	2.95	30.84	2.10	35.63	2.16	39.84	2.94	42.06	3.94
	20°C in LSW	20.30	2.88	31.36	3.18	36.90	2.03	39.73	2.58	44.01	3.48

*S: strength, CV: coefficient of variation.

specimen size two opposing effects must be considered.

Since the dimensions of the specimens used in this study are close to each other, the effect of curing on the measured strength may be negligible. The compressive strength of larger specimens (50 mm) would have expected to be smaller than the smaller specimens (40 mm). However, measured compressive strength of 50 mm cubic specimens is about 22% higher than compressive strength of 40 mm cubic specimens (Figure 3).

Flexural strength

The changes in the flexural strength differ both qualitatively and quantitatively from corresponding changes in compressive strength and underlying mechanism is also different. Even a short drying of a concrete beam immediately before testing produces a moisture gradient in the specimen which in turn creates tensile stresses in the surface layer. Therefore a short, (example, 30 min.) pre-test drying produces a sizeable reduction in the flexural strength (Popovics, 1986).

According to test data obtained in this study flexural strength is more sensitive to humidity than compressive strength (Figure 4). On contrary to compressive strength, the measured flexural strength of the specimens cured at 15°C, 75% RH condition is approximately 20% smaller than the ones cured in water and tested in surface-dry

Table 3. The parameters of the equations.

Specimen	Curing condition	A	B	R
Compressive strength of 50 mm cubic specimens	4℃, 75% RH	6.45	15.08	0.92
	15℃, 55% RH	2.70	19.18	0.78
	15℃,75% RH	12.27	14.02	0.97
	32℃,35% RH	1.91	25.87	0.81
	20℃ in TW	11.47	13.55	0.99
	20℃ in LSW	12.16	14.78	0.99
Compressive strength of prismatic specimens	4℃,75% RH	5.21	13.70	0.93
	15℃,55% RH	2.24	16.73	0.75
	15℃,75% RH	9.69	11.43	0.98
	32℃,35% RH	1.55	21.86	0.84
	20℃ in TW	8.54	13.63	0.99
	20℃ in LSW	8.66	14.26	0.99
Compressive strength of prismatic specimens	4℃,75% RH	0.79	3.3	0.98
	15℃,55% RH	1.26	3.64	0.95
	15℃,75% RH	0.31	3.65	0.58
	32℃,35% RH	0.53	4.52	0.92
	20℃ in TW	1.23	4.84	0.97
	20℃ in LSW	1.20	5.10	0.98

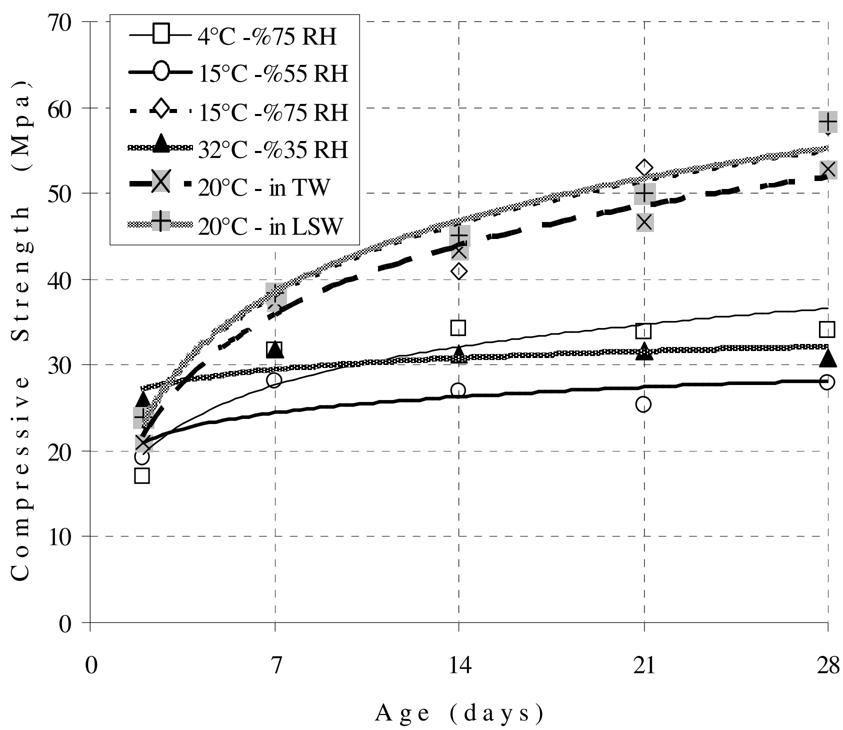

Figure 1. The compressive strength of 50 mm cubic specimens.

condition. Another contrast to compressive strength, at all ages, the maximum flexural strength was gained by the specimens that were cured in water. The measured flexural strength of the specimens that were cured at 4℃, 75%RH is 20% smaller than the ones cured at 32℃, 35%RH at 2 days, but is equal to them at 28 days. The smallest values of flexural strength of specimens were determined under 15℃, 55%RH curing at all days.

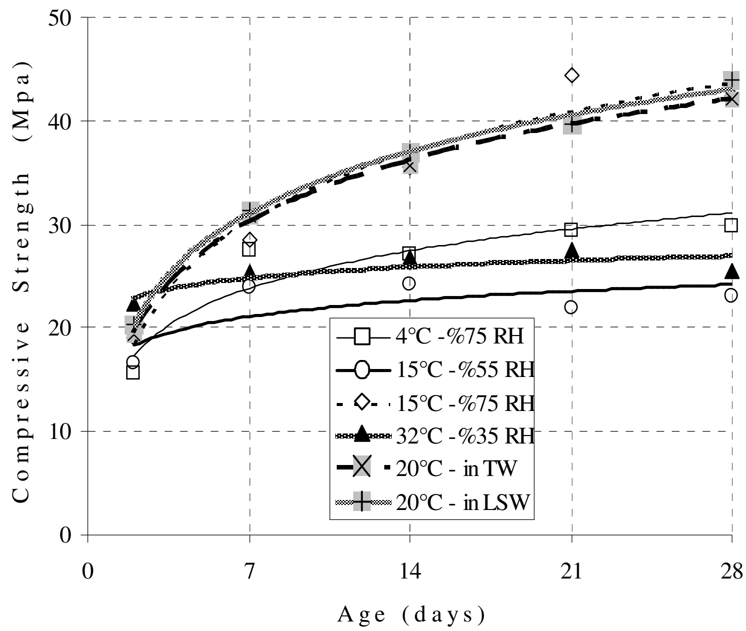

Figure 2. The compressive strength of prismatic specimens.

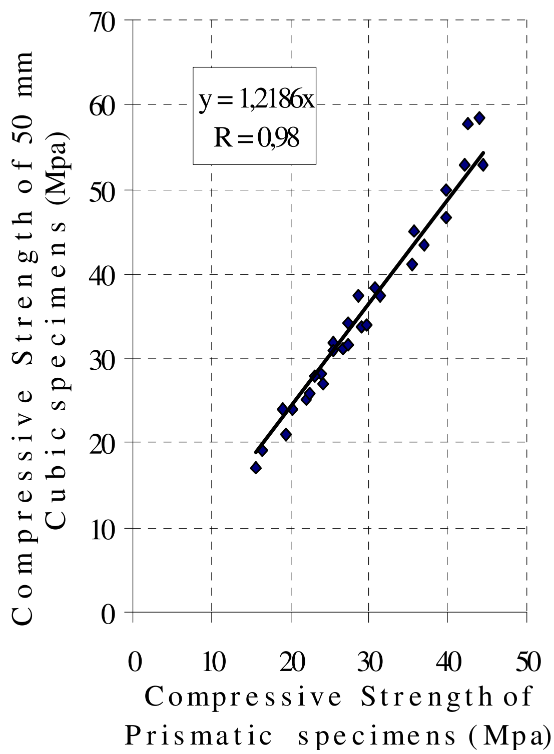

Figure 3. Compressive strength of 50 mm cubic specimens versus compressive strength of prismatic specimens.

Effect of pH degree of water

When the specimens put into curing water, the pH degree of tap water is in the range from 7.0 to 8.0 where the pH degree of lime saturated water is in the range from 12.0 to 13.0. But after 12 h the pH degree of the water in the curing tank became 12 to 13. The reason of increasing of the pH degree of the water is leaching of $Ca(OH)_2$. During the curing time the tap water was not changed and the pH degree of the water did not change. Also with leaching of the $Ca(OH)_2$ strength of specimens decreases. The reason of this condition is the leaching of $Ca(OH)_2$ that is one of the products of hydration of cement. As migration of $Ca(OH)_2$ from solid body of specimen the solid contents of hydrated cement paste decreases. So that the strength of specimen decreases. In this research the specimens cured in tap water and lime saturated water have approximately equal compressive and flexural strength values at all curing ages. Indeed strength of specimens cured in lime saturated water is a little higher than specimens cured in tap water. The strength of the specimens did not decrease considerably because the tap water was not changed and the pH degrees of the curing waters were same after 12 h.

Conclusions

1. The well-known effect of temperature on the mechanical properties of cementitous materials was observed under high relative humidity conditions especially at early ages if there is sufficient water in the capillary pores even under low relative humidity conditions. The early strength values were higher at warmer conditions compared to the cooler conditions. The

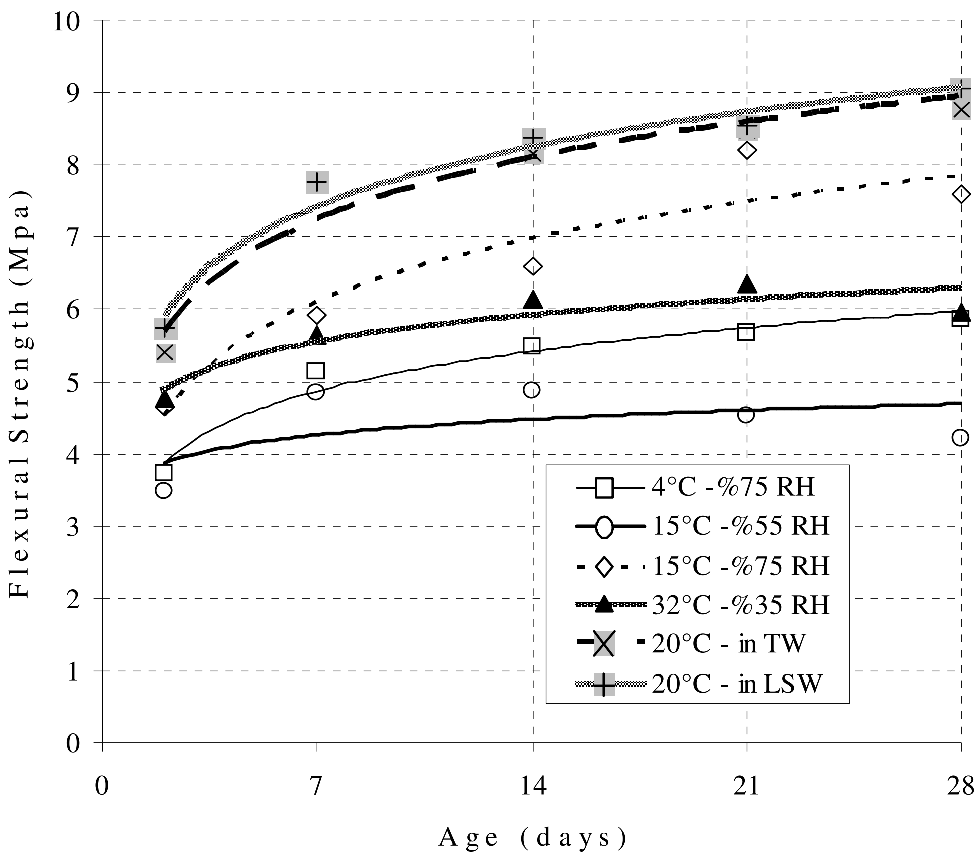

Figure 4. The flexural strength of prismatic specimens.

hydration process and increase of strength developed continuously under high relative humidity regimes up to 75%. The strength development in hot and cold regimes with high humidity has been measured in accordance with technical literature.

However, the strength development has not been observed under 75% relative humidity. This result indicates that well-known maturity formula which is a function of time interval and temperature is not valid for the climates with relative humidity values lower than 75%.

2. Flexural strength is more sensitive to curing conditions especially to relative humidity than compressive strength. The lower relative humidity values cause decreases on flexural strengths.

3. Since the experiments are made on mortar specimens, the determined values and results may not be directly compatible to concrete specimens. But as the dimensions of the specimens that were used in this study are approximately equal to the cover of reinforced concrete elements, the results may be applicable to reinforced concrete concerning the durability problems. Especially penetration of the aggressive chemicals and corrosion of reinforcement is adversely affected by quality of cover.

4. Critical climatic conditions created in study caused decreases up to 40% in compressive strength and 30% in flexural strength compared to standard curing. This means that poor curing conditions and unproper climatic conditions may create significant undesirable results.

5. On a contrary to the assumption “smaller specimens have higher compressive strength than bigger specimens”, the compressive strength of 50 mm cubic specimens is about 22% higher than compressive strength of 40 mm prismatic cubic specimens due to the experiment method.

6. In this research the specimens cured in tap water and lime saturated water have approximately equal compressive and flexural strength values separately at all curing ages. Indeed strength of specimens cured in lime saturated water is a little higher than specimens cured in tap water. The strength of the specimens did not decrease considerably because the tap water was not changed and the pH degrees of the curing waters were same after 12 h.

ACKNOWLEDGEMENTS

This paper has been prepared by using the results of a project that is funded by Research and Development Institute of Turkish Cement manufacturers Association and Dokuz Eylul University. The author also expresses his sincere gratitude to the personnel of the Institution

and University.

REFERENCES

ASTM International (2002). ASTM C109 Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens).

Baradan B, Yazıcı H, Ün H (2002). Durability of Reinforced Concrete Structures, Dokuz Eylul University, Publication p. 298, İzmir, Turkey, (in Turkish).

Cebeci OZ (1987). "Strength of Concrete in Warm and Dry Environment", Mater. Struct,, 20(118): 270-272.

Garcia EJI, Sharp JH (1998). Effects of Temperature on Hydration of Main Clinkers Phases in Portland Cements: Part I, Neat Cements, Cem. Concr. Res., 28(9): 245-258.

Gardner NJ, Sau PL, Cheung MS (1988). Strength Development and Durability of Concretes Cast and Cured at 0°C, ACI Mater. J., 85 (6): 529-536.

Ho DWS, Cui QY, Ritchie DJ (1989). Influence of Humidity and Curing Time on the Quality of Concrete, Cem. Concr. Res., 19(3): 457-464

Kanna V, Olsan RA, Jennings HM (1998). Effect of Shrinkage and Moisture Content on Physical Characteristics of Blended Cement Cem. Concr. Res., 28(10): 1467-1277.

Klieger P (1958). "Effect of Mixing and Curing Temperatures on Concrete Strength", ACI J., 54(12): 1063-1081.

Neville AM (1999). Properties of Concrete, Pearson Education Ltd., London, pp. 482-529.

Patel RG, Killoh DC, Parrott LJ, Gutteridge WA (1988).Influence of Curing at Different relative Humidities upon Compound reactions and Porosity of Portland Cement Paste, Mater. Struct., 21(123): 192-197.

Popovics S (1986). Effect of Curing Method and Final Moisture Condition on Compressive Strength of Concrete", ACI J., 83(4): 650-657.

Powers TC (1947). A Discussion of cement hydration in relation to the curing of concrete, Proc. Highway Research Board Washington DC. 27: 178-188.

Price WH (1951). "Factors influencing concrete strength" J. Am. Concrete Institut., 47: 417-432,

Soroka I, Baum H (1994). Influence of Specimen Size on Effect of Curing Regime on Concrete Compressive Strength, J. Mater .Civil Eng., 6(1): 15-22.

Spears RE (1983). The 80 Percent Solution to Inadequate Curing Problems. Concr. Int., 5: 15-18

Turkish Standards Institution (2009). Turkish Standard TS 706 EN 12620 "Aggregates for concrete", Turkey.

Turkish Standards Institution (2009). Turkish Standard TS EN 196-1 "Methods of testing cement - Part 1: Determination of strength", Turkey.