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Effectiveness of Steam Curing on Repairing Early Age Mortar Damages

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Keywords
Portland Cement Mortar,
Steam Curing,
Healing,
Early Age Mechanical Properties.

Abstract: Standard, steam and air curing methods were investigated in the scope of presented study to assess the healing performance of early age mortar damages. Compressive stress levels of 50, 75, 90 and 100 % of strength were adapted to Portland cement mortar or blended cement mortar specimens at early ages. Test results exhibited that preloading level under 90 % of instantaneous strength until 4 days, did not affect the ultimate strength for standard cured specimens. On the contrary, results obtained from air cured specimens preloaded after 2 days were almost equal or greater than that of control specimens. Surprisingly, steam curing application could not provide expected recuperation; however, less variable strength results were obtained. Blended cement mortar specimens achieved better results with steam curing process. Besides, it was possible to reach 53 MPa compressive strength by selecting a proper curing treatment even in the case of full damage.

Erken Dönem Harç Hasarlarının Tamirinde Buhar Kürünün Etkinliğinin Araştırılması

Anahtar Kelimeler
Portland Çimentosu Harcı,
Buhar Kürü,
İyileşme,
Erken Dönem Mekanik Özellikler.

Özet: Bu çalışma kapsamında erken dönemde oluşan çimento harcı hasarlarının iyileştirilmesinde standart kür, buhar kürü ve hava kürü yöntemlerinin etkinliği araştırılmıştır. Portland çimentosu ve katkılı çimento harçlarına 1., 2., 4. ve 7. günlerde basınç dayanımlarının %50, 75, 90 ve 100 seviyelerinde gerilme uygulanmıştır. Test sonuçları 4. güne kadar %90'dan daha düşük ön yükleme uygulamasının standart kürlü numunelerin nihai dayanımlarını etkilemediğini göstermiştir. Diğer yandan 2 günden sonra ön yükleme yapılmış ve havada kür edilmiş numunelerin test sonuçları kontrol numunelerine eşit veya daha büyüktür. Buhar kürü uygulaması beklenen mukavemet artışını sağlamamış ancak daha az değişken dayanım sonuçları elde edilmiştir. Katkılı çimento ile üretilmiş harç numunelerinde buhar kürü uygulaması ile daha iyi sonuçlar elde edilmiştir. Uygun kür yönteminin seçimi ile tam hasar durumunda bile 53 MPa basınç dayanımı sonucuna ulaşmak mümkün görünmektedir.

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1. Introduction

Cracks existing in reinforced concrete structures affect the structure in two manners. On one hand, reduced strength put the mechanical safety at a great risk; on the other hand increased permeability shortens the service life of the structure. In most cases, both mechanisms synergistically affect each other. Therefore, healing of the cracks either in micro or macro scale has a great importance in terms of structural safety, durable service life and economical costs.

However, early age concrete damage would be a very difficult issue to solve the problem without any lost in economy or a period of time. Deflection of molds or early demolding of formworks, various shrinkage mechanisms, thermal gradients, hydration process and etc. were main causes of early age concrete cracks. In many cases there would be no chance to repair the major damages of reinforced concrete elements. Minor cracks could be eliminated by healing or injection techniques.

Recent years great efforts being made on developing efficient methods to repair the concrete cracks or damages. Many researchers have concluded that small cracks in concrete can heal by autogenous healing phenomenon [1-7]. Alyousif et al. noted that up to 92 % of healing was determined depending on the type of the mixture and curing history [8]. In general, the self-healing mechanism of an unspecific concrete is related to the chemical reactions of unhydrated particles of cement and carbonation process [2, 3, 9]. Healing capacity for this phenomenon is restricted with age of concrete and the crack width [10, 11].

Repairing the damage with agents added the composite at initial mixing stage were being deeply considered. Bacteria induced mineral precipitation to improve the healing capacity was under investigation with disadvantages such as, the bacteria would die over time even encapsulated or guard protected due to the harsh environment inside the concrete. In addition, moist environment was not guaranteed that have a great influence on the crack repair effect [12]. The addition of healing agents such as bacteria and/or chemical compounds to the paste may result in unwanted decrease of strength properties [13].

Chemical expansive additives show the better crack healing performance by filling the cracks and enhancing the mechanical properties [14]. However, an additional self-cracking risk could be occurred by restrained deformation unless the dosage was well proportioned [15].

Being in such a tight situation, extending the curing time or enhancing the efficiency of curing method could be an alternative way. Steam curing of cement and concrete is a well-known thermal treatment process that greatly increases the early age strength. However, a loss in ultimate strength values would be expected [16, 17]. This commonly used technique in precast industry could sometimes be selected to activate the pozzolanic material to form secondary calcium silicate hydrate gel which increases the strength value of the composite [18].

In the present study, curing conditions and particularly steam curing application have been investigated with regard to strength gain capacities of Portland cement mortars. Two types of Portland cements mortars were used in the assessment of damage degree and preloading age variations. Mechanical test results and optical microscope observations were evaluated comparatively.

2. Experimental Study

An experimental program has been carried out according to following details. The experimental variables include cement type (CEM I 42.5 R and CEM-II/B-M(L-W) 42.5 R), age of preliminary loading (1, 2, 4 and 7 days) and curing method (standard water curing, atmospheric steam curing and air curing). Compressive strength values of preloaded specimens were investigated at 28th day.

2.1. Materials

An ordinary type Portland cement CEM I 42.5 R and a blended cement CEM-II/B-M(L-W) 42.5 R were used in this study. The chemical composition and physical properties of cementitious materials are given in Table 1.

Table 1. Chemical composition and physical properties of cementitious materials.

Composition / Property	CEM-I 42.5R	CEM-II/B-M(L-W) 42.5R
CaO (%)	63.27	53.48
SiO_2 (%)	19.04	23.58
Al_2O_3 (%)	5.65	8.77
Fe_2O_3 (%)	2.21	2.64
MgO (%)	1.27	1.37
SO_3 (%)	3.50	3.46
Na_2O (%)	0.19	0.19
K_2O (%)	0.93	0.99
F. CaO (%)	1.00	1.72
I.R. (%)	0.73	11.11
L.O.I. (%)	3.40	5.18
Specific gravity (gr/cm^3)	3.11	3.00
Blaine (cm^2/gr)	3820	4443
>32µm (%)	28.37	11.98
>45µm (%)	15.28	4.37
>90µm (%)	2.56	0.25
Initial set (min.)	158	173
Final set (min.)	200	223
Expansion (mm)	1.00	1.60

Crushed limestone sand was used as aggregate with the specific gravity of 2.65. Maximum aggregate size was 4 mm and the gradation curve of limestone was very close to standard silica sand.

Same mixture proportions were used in mortar preparation works for two types of cement. Water/cement ratio and aggregate/cement ratio were 0.5 and 3.0, respectively.

Test results and the abbreviations in specimen codes which denote cement type, age of preliminary loading, stress percentage at preliminary loading and curing method after loading, respectively, have been given in Table 2 and 3.

2.2. Procedure

The mixtures were prepared in a standard vertical axis Hobart mixer. Dry materials were mixed with the agitating speed of 60 rpm for about 1 minute. After water addition, mixtures were mixed for about 1 minute with the agitating speed of 60 rpm and then 120 rpm, respectively. The consistencies of mixtures were in the range of 115-120 mm according to mini slump flow test. Casting and compaction of 5x5x5 cm cubic specimens realized by hand operations and vibration.

The specimen moulds were kept in a humid chamber for 24 h at room temperature of 20 °C. After demoulding, specimens were exposed to standard water curing up to preliminary loading age.

Early age loading tests have been applied to specimens with a load controlled testing machine. Firstly, compressive strength values have been determined. Tests were terminated at the point of 5 % load reduction after the peak load. Compressive stress values of 90, 75 and

50 % of compressive strength have been applied to next group of the specimens. Then, post curing stage has been started. Standard water curing at 20 °C was performed to one group of specimens until 28th day. Another group of specimens have been subjected to steam curing at 100 °C. Target temperature has been reached within 6 hours and heat treatment duration was selected for 12 hours. Controlled cooling period took 4 hours. Specimens were kept in laboratory atmosphere until 28th day at the temperature range of 15-20 °C with the relative humidity of 50-60 %. Last group of specimens have been exposed to laboratory atmosphere up to 28th day. Average of three identical test results was used to evaluate the mechanical performance.

3. Results and Discussion

Applied early age stresses and compressive strength values of the specimens at 28th day were presented in Table 2 for CEM I specimens and in Table 3 for CEM II specimens.

Compressive strength developments for CEM I and CEM II specimens are shown in Figure 1. 28th day compressive strength of CEM I specimens was measured as 60.1 MPa. Relative strengths for 1, 2, 4 and 7 days were 48, 64, 73 and 81 % respectively. Strength value for blended cement was 55.8 MPa, and relative strengths were 32, 46, 67 and 73 for corresponding ages. As expected Portland cement exhibit greater strength values for early ages. Blended cement CEM II specimens made up the differences in strength values at 28th day.

Compressive strength value variations of standard cured CEM I specimens after various stress application at different loading ages were given in Figure 2.

It can be said that pre-stressing level has a great importance on ultimate strength. Also it seems that it has a threshold level between 90-100 %. As expected strength gain for fully damaged specimens was kept at low level. Lowering the preloading level under 90 % of instantaneous strength, do not affect the ultimate strength especially for the specimens preloaded at early ages. Compressive strength values of specimens pre-loaded at 1 or 2 day were about 60 MPa level, while 28th day strength of water cured specimens was 60.1 MPa without any preloading. Consequently, no mechanically permanent damage was observed for these specimens.

On the other hand, for preloading level of 50-90 % increase in preloading age beyond 2 days, decreased the ultimate strength values about 5 MPa (8 % strength loss) for 4 days and 6-10 MPa (10-16 % strength loss) for 7 days.

Zhong and Yao noted that self-healing of concrete was markedly influence by its damage degree and there exists a damage degree threshold which depends on materials. The authors also concluded that the threshold for normal strength concrete was higher than that for high strength concrete [11].

From the view point of loading age, it can be said that early preloaded specimens were less affected from the damage. Two reasons have effect upon this phenomenon. Firstly, due to early time of hydration compressive strength values were lower, hence applied stress were lower. Most importantly, at the early ages of hydration process, much non-hydrated cementitious particles capable to fill the cracks were still present around the damaged area.

Table 2. Test results of CEM I specimens

Specimen code	Cement type	Preloading age (day)	Stress level (%)	Stress (MPa)	Curing type	28th day strength (MPa)
I-1-50-STD	I	1	50	14.5	STANDARD	61.3
I-1-75-STD	I	1	75	21.7	STANDARD	60.6
I-1-90-STD	I	1	90	26.0	STANDARD	60.5
I-1-100-STD	I	1	100	29.5	STANDARD	51.7
I-2-50-STD	I	2	50	19.1	STANDARD	58.2
I-2-75-STD	I	2	75	28.6	STANDARD	60.5
I-2-90-STD	I	2	90	34.4	STANDARD	59.1
I-2-100-STD	I	2	100	37.1	STANDARD	47.6
I-4-50-STD	I	4	50	21.9	STANDARD	55.5
I-4-75-STD	I	4	75	32.9	STANDARD	56.4
I-4-90-STD	I	4	90	39.5	STANDARD	55.7
I-4-100-STD	I	4	100	46.6	STANDARD	48.8
I-7-50-STD	I	7	50	24.3	STANDARD	52.7
I-7-75-STD	I	7	75	36.4	STANDARD	50.4
I-7-90-STD	I	7	90	43.7	STANDARD	54.5
I-7-100-STD	I	7	100	50.2	STANDARD	45.8
I-1-50-STM	I	1	50	14.5	STEAM	41.9
I-1-75-STM	I	1	75	21.7	STEAM	41.6
I-1-90-STM	I	1	90	26.0	STEAM	42.7
I-1-100-STM	I	1	100	28.8	STEAM	36.7
I-2-50-STM	I	2	50	19.1	STEAM	45.1
I-2-75-STM	I	2	75	28.6	STEAM	43.4
I-2-90-STM	I	2	90	34.4	STEAM	42.2
I-2-100-STM	I	2	100	38.9	STEAM	37.7
I-4-50-STM	I	4	50	21.9	STEAM	46.9
I-4-75-STM	I	4	75	32.9	STEAM	43.4
I-4-90-STM	I	4	90	39.5	STEAM	43.8
I-4-100-STM	I	4	100	42.9	STEAM	37.3
I-7-50-STM	I	7	50	24.3	STEAM	45.3
I-7-75-STM	I	7	75	36.4	STEAM	42.1
I-7-90-STM	I	7	90	43.7	STEAM	42.7
I-7-100-STM	I	7	100	46.8	STEAM	34.7
I-1-50-AIR	I	1	50	14.5	AIR	50.7
I-1-75-AIR	I	1	75	21.7	AIR	54.5
I-1-90-AIR	I	1	90	26.0	AIR	51.9
I-1-100-AIR	I	1	100	28.5	AIR	45.9
I-2-50-AIR	I	2	50	19.1	AIR	59.9
I-2-75-AIR	I	2	75	28.6	AIR	59.7
I-2-90-AIR	I	2	90	34.4	AIR	59.2
I-2-100-AIR	I	2	100	39.5	AIR	53.0
I-4-50-AIR	I	4	50	21.9	AIR	62.4
I-4-75-AIR	I	4	75	32.9	AIR	60.6
I-4-90-AIR	I	4	90	39.5	AIR	61.7
I-4-100-AIR	I	4	100	42.1	AIR	51.2
I-7-50-AIR	I	7	50	24.3	AIR	59.2
I-7-75-AIR	I	7	75	36.4	AIR	58.6
I-7-90-AIR	I	7	90	43.7	AIR	58.2
I-7-100-AIR	I	7	100	48.8	AIR	50.3

Table 3. Test results of CEM II specimens

Specimen code	Cement type	Preloading age (day)	Stress level (%)	Stress (MPa)	Curing type	28th day strength (MPa)
II-1-50-STD	II	1	50	8.6	STANDARD	52.1
II-1-75-STD	II	1	75	13.0	STANDARD	50.6
II-1-90-STD	II	1	90	15.6	STANDARD	54.3
II-1-100-STD	II	1	100	17.4	STANDARD	46.7
II-2-50-STD	II	2	50	13.0	STANDARD	51.2
II-2-75-STD	II	2	75	19.5	STANDARD	49.3
II-2-90-STD	II	2	90	23.4	STANDARD	49.0
II-2-100-STD	II	2	100	27.1	STANDARD	46.3
II-4-50-STD	II	4	50	18.8	STANDARD	54.5
II-4-75-STD	II	4	75	28.3	STANDARD	55.2
II-4-90-STD	II	4	90	33.9	STANDARD	57.9
II-4-100-STD	II	4	100	38.3	STANDARD	46.3
II-7-50-STD	II	7	50	20.3	STANDARD	52.3
II-7-75-STD	II	7	75	30.5	STANDARD	52.8
II-7-90-STD	II	7	90	36.6	STANDARD	53.3
II-7-100-STD	II	7	100	40.3	STANDARD	45.8
II-1-50-STM	II	1	50	8.6	STEAM	44.3
II-1-75-STM	II	1	75	13.0	STEAM	45.1
II-1-90-STM	II	1	90	15.6	STEAM	47.0
II-1-100-STM	II	1	100	18.3	STEAM	38.3
II-2-50-STM	II	2	50	13.0	STEAM	44.2
II-2-75-STM	II	2	75	19.5	STEAM	44.5
II-2-90-STM	II	2	90	23.4	STEAM	43.9
II-2-100-STM	II	2	100	25.5	STEAM	38.6
II-4-50-STM	II	4	50	18.8	STEAM	48.9
II-4-75-STM	II	4	75	28.3	STEAM	48.3
II-4-90-STM	II	4	90	33.9	STEAM	48.5
II-4-100-STM	II	4	100	37.8	STEAM	39.5
II-7-50-STM	II	7	50	20.3	STEAM	49.8
II-7-75-STM	II	7	75	30.5	STEAM	48.7
II-7-90-STM	II	7	90	36.6	STEAM	48.5
II-7-100-STM	II	7	100	41.0	STEAM	37.9
II-1-50-AIR	II	1	50	8.6	AIR	44.4
II-1-75-AIR	II	1	75	13.0	AIR	47.6
II-1-90-AIR	II	1	90	15.6	AIR	50.0
II-1-100-AIR	II	1	100	18.6	AIR	42.4
II-2-50-AIR	II	2	50	13.0	AIR	49.0
II-2-75-AIR	II	2	75	19.5	AIR	50.4
II-2-90-AIR	II	2	90	23.4	AIR	52.8
II-2-100-AIR	II	2	100	25.3	AIR	45.0
II-4-50-AIR	II	4	50	18.8	AIR	57.0
II-4-75-AIR	II	4	75	28.3	AIR	57.8
II-4-90-AIR	II	4	90	33.9	AIR	59.4
II-4-100-AIR	II	4	100	37.0	AIR	48.0
II-7-50-AIR	II	7	50	20.3	AIR	61.7
II-7-75-AIR	II	7	75	30.5	AIR	59.4
II-7-90-AIR	II	7	90	36.6	AIR	60.5
II-7-100-AIR	II	7	100	40.6	AIR	48.5

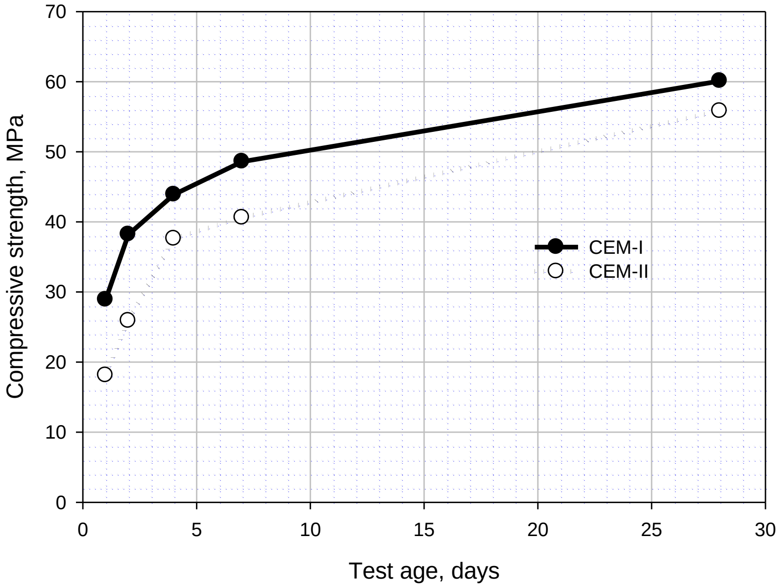

Figure 1. Compressive strength development of standard cured specimens

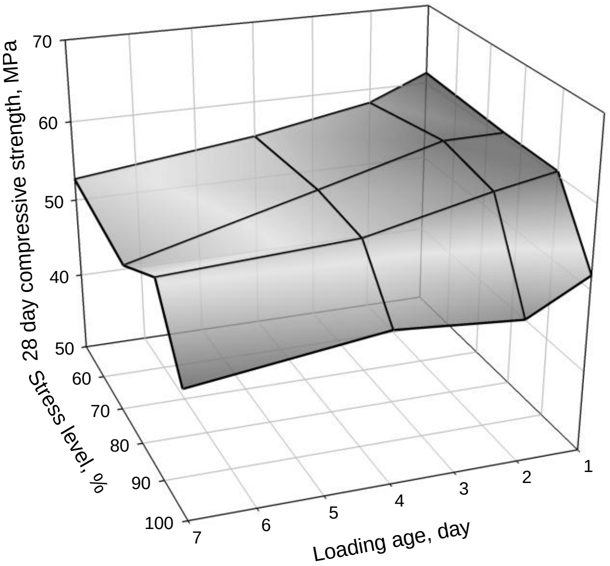

Figure 2. Compressive strength values of standard cured CEM I specimens after various stress application at different loading ages

Abdel-Jawad and Haddad reported the effect of early over-loading of concrete on its strength development [10]. Concrete and mortar samples were subjected to different loading levels at ages of 8, 16, 24 and 72 hours. The samples were then retested, along with control specimens, at ages of 7, 28, and 90 days. The results indicate that loading concrete, beyond 8 hours after casting, up to 90 % of its compressive strength has no effect on later strength development. However, loading concrete up to failure resulted in strength loss between 10 % to 50 %, depending on age at time of loading, age at time of retesting and curing conditions.

Compressive strength value variations of steam cured CEM I specimens after various stress application at different loading ages were given in Figure 3.

Figure 3 shows the results that steam curing after preloading could not provide expected contribution. Ultimate strength values were in the range of 41-46 MPa for 50, 75 and 90 % preloading levels, independent from the preloading age. Fully damaged i.e. 100 % preloaded specimens had 35-37 MPa compressive strength after steam curing application.

Steam curing application after preloading caused lower 28th day compressive strength values but more stable results. Variation in preloading age or in preloading level did not greatly affect the strength gain after steam curing. This argument was in conformity with fact that steam curing causes porous, heterogenic microstructure in Portland cement systems. By an impressed thermal treatment a dense microstructure forms around the cement particles. On the contrary, capillary pores could not filled by hydration products. Thus a strength value less than the strength capacity of composite could be obtained.

Steam curing application after preloading thought to cause same manner even at relatively later ages.

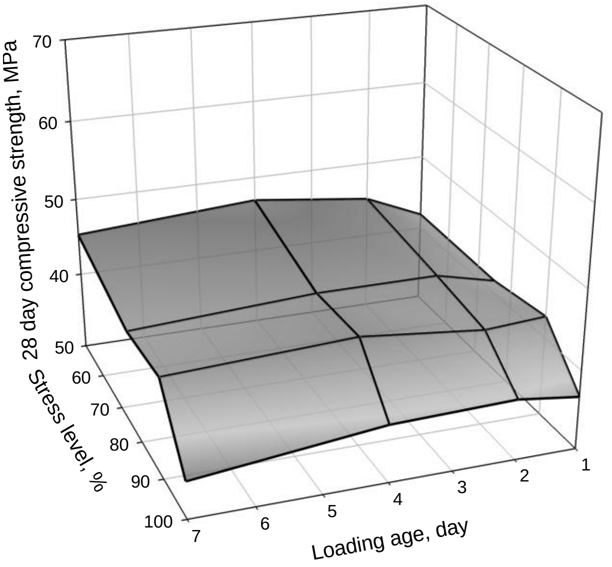

Figure 3. Compressive strength values of steam cured CEM I specimens after various stress application at different loading ages

Figure 4 shows the result of air cured specimens after preloading. In this series, specimens were water cured until first loading and preloaded up to target strength percent then kept in air until 28th day. Thus curing process was very limited and hydration environment was altered after a short period of time especially for 1st day of preloading age.

Interestingly strength gain of these series of specimens was considerably greater compared to steam cured series. Two mechanisms were thought to be activated the strength gain. First, the humidity inside the specimen maintained the hydration progress. Compared to steam curing process a more homogenous microstructure could be achieved. The second was drying process. It is well known that dry samples exhibits 10-15 % greater values in terms of measured strength.

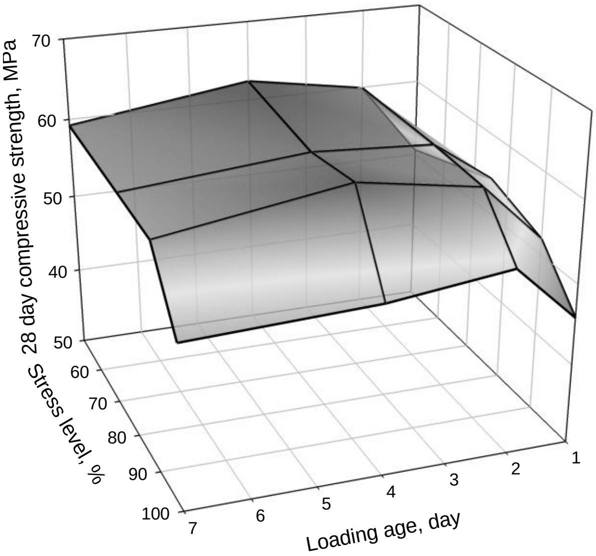

Figure 4. Compressive strength values of air cured CEM I specimens after various stress application at different loading ages

Compared to standard curing, air cured specimens which were preloaded relatively at later ages for example 4 and 7 days, gained greater strength values. The crack free areas were well cured, and after preloading crack surfaces may get closer by drying. Besides, ongoing hydration progress with inner humidity strengthened the crack zones of the composite. In this way, even fully damaged specimens at 7th day indicated 50.3 MPa of compressive strength at 28th day.

Compressive strength value variations versus preloading age and stress level for standard cured CEM II specimens were given in Figure 5. Compared to CEM I specimens the only difference was the lower final strength values for the specimens those preloaded at 1st and 2nd day. Later age of preloading caused similar compressive strength values with CEM I specimens. In fact a greater strength gain was occurred especially for early ages. For example, in the case of preloading a compressive stress of 100 % of instantaneous strength at 1st day, resulted in 29.3 MPa strength gain (17.4 MPa to 46.7 MPa) for CEM II, while the corresponding strength gain value was 22.2 MPa (29.5 MPa to 51.7 MPa) for CEM I.

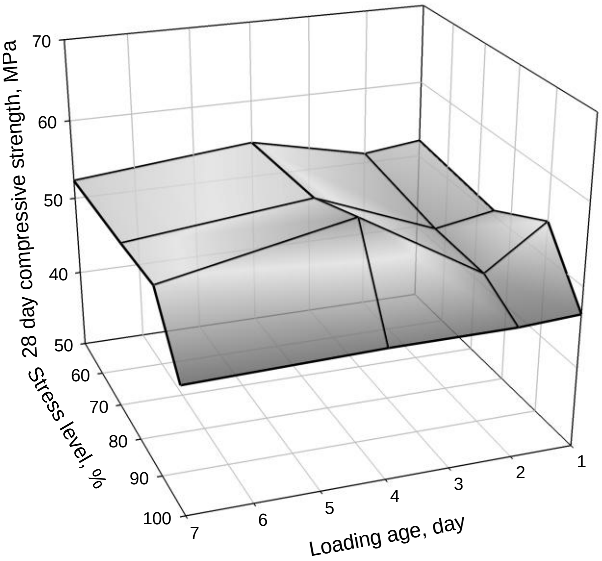

Figure 5. Compressive strength values of standard cured CEM II specimens after various stress application at different loading ages

Figure 6 depicts the compressive strength values of steam cured CEM II specimens after various stress application at different loading ages. Steam cured blended cement mortar specimens after preloading exhibited same behavior same as ordinary Portland cement mortar specimens. The only difference was somewhat greater compressive strength values after 28 days. This situation was an indicator that impressive thermal treatment provided more benefits for blended cement. It was supposed that, this contribution was provided by higher activation of pozzolanic fly ash at elevated temperatures during steam curing process.

Compressive strength values of air cured CEM II specimens after various preloading are represented in Figure 7.

A dramatic reduction in 28th day compressive strength values have been observed in blended cement mortars at early age preloaded specimens compared to ordinary Portland cement mortar specimens. Insufficient curing of blended specimens resulted in a sharp strength loss even they were not fully damaged.

On the other hand, compressive strength values of the specimens preloaded without full damage at 7 days were above the 60 MPa.

In the case of 100 % preloading, 42-48 MPa compressive strength values have been achieved with an increasing trend versus preloading age.

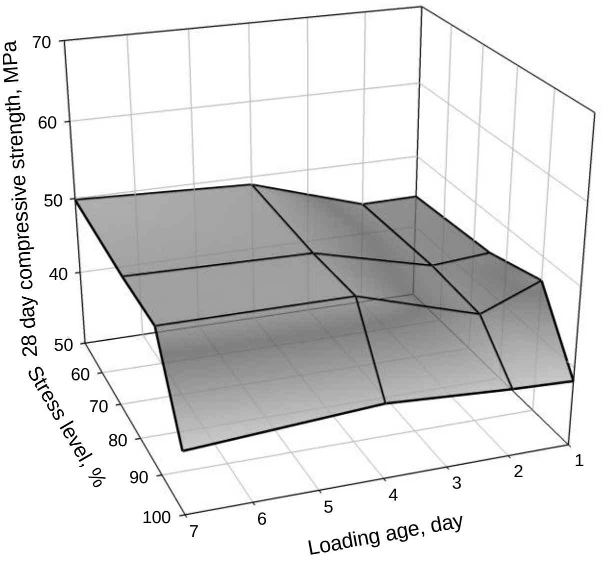

Figure 6. Compressive strength values of steam cured CEM II specimens after various stress application at different loading ages

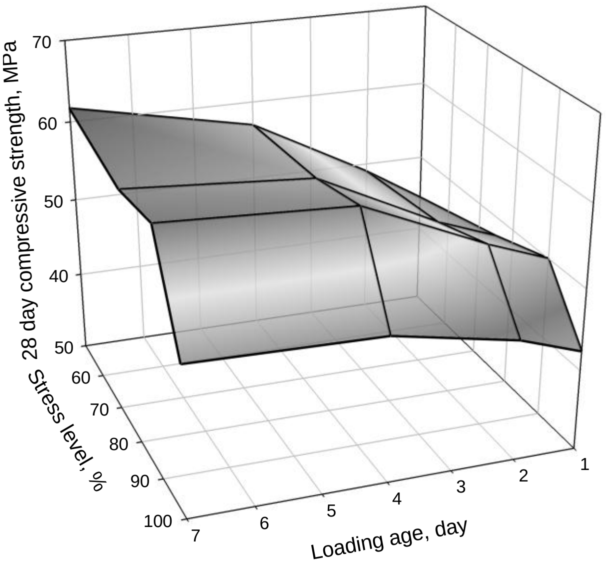

Figure 7. Compressive strength values of air cured CEM II specimens after various stress application at different loading ages

To perform a brief microstructural observation an optical digital microscope with 250x magnification was used. Micrograph of standard cured CEM-I specimen preloaded at 1st day given in Figure 8-a. It can be seen that cracks were healed during the standard curing process. The image was taken from the surface of cubic specimen after 28th day final test. Crack opening was occurred again after the final test. Healing product thickness was measured approximately 75 µm in each side of the crack.

Aggregate-matrix transition zone of the same group of the specimen was shown in Figure 8-b which was taken before the 28th day final test. Healing products almost fulfilled the crack around the sand particle. A small part of the crack still remains unfilled. Detailed discussion for the similar healed cracks could be found in the study by Hilloulin et al. [19].

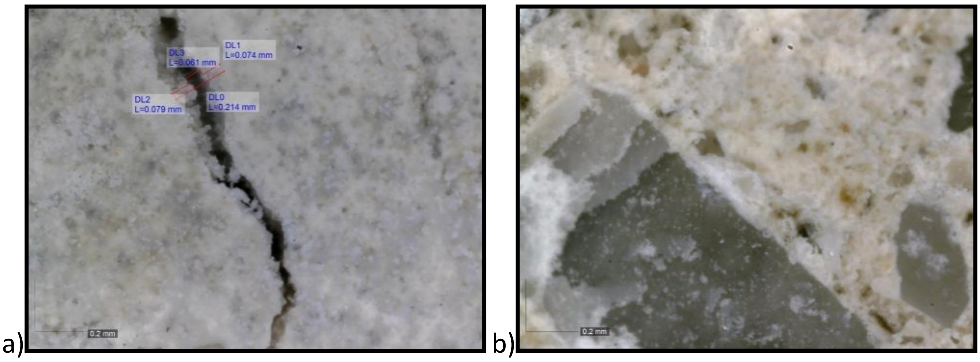

Figure 8. Micrographs of CEM-I specimens which were standard cured after preloading at 1st day up to 100 % of compressive strength a) surface after 28th day final test b) interior before 28th day final test.

Micrographs of the steam cured specimens after preloading at 1st day up to 100 % of compressive strength are given in Figure 9-a for CEM-I and in Figure 9-b for CEM-II. It was revealed that 100 °C steam curing for 12 h could not repair the cracks.

Micrographs of CEM-I specimens which were air cured after preloading at 1st day up to 100 % of compressive strength were given in Figure 10-a for the surface and in Figure 10-b for interior before 28th day final test. In a similar manner with steam curing process, air curing process could not heal the cracks.

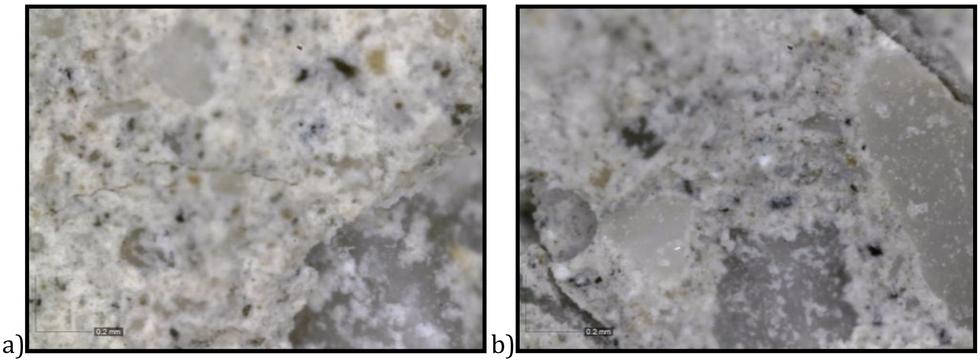

Figure 9. Images of steam cured specimens preloaded at 1st day up to 100 % of compressive strength a) CEM-I b) CEM-II.

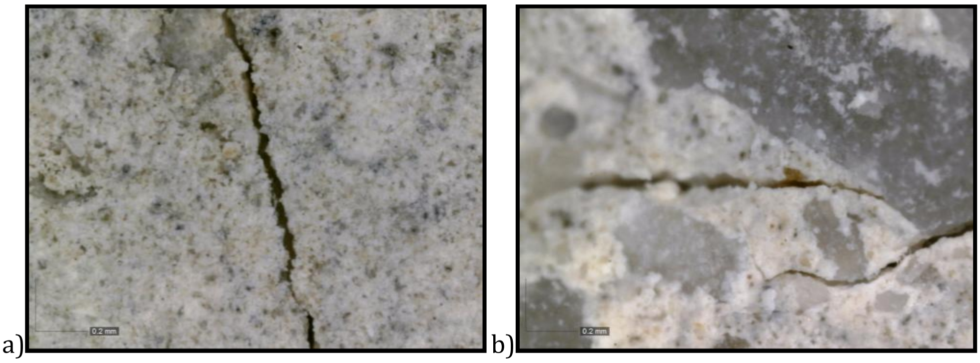

Figure 10. Micrographs of CEM-I specimens which were air cured after preloading at 1st day up to 100 % of compressive strength a) surface before 28th day final test b) interior before 28th day final test.

4. Conclusions

The following items can be drawn from the results of given experimental study.

- Pre-stressing level has a great importance on ultimate strength. Also it seems that it has a threshold level between 90-100 %.
- Lowering the preloading level under 90 % of instantaneous strength, do not affect the ultimate strength of standard cured specimens especially for the preloading at early ages.
- On the contrary, results obtained from air cured specimens preloaded at relatively later ages were almost equal or greater than that of control specimens.
- Steam curing application after preloading caused lower 28th day compressive strength values but more stable results. Variation in preloading age or in preloading level did not greatly affect the strength gain after steam curing. It can be said that, steam curing after a damage had a limited efficiency but provide closer strength values with respect to preloading age or preloading stress level.
- Blended cement mortar specimens achieved better results with steam curing process.

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