EFFECT OF ATMOSPHERIC STEAM CURING PARAMETERS ON CONCRETE STRENGTH AND DURABILITY

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مُسْـتَخْلـَص

معالجة الخرسانة ببخارالماء -تحت الضغط الجوي- توفر الرطوبة وتزيد درجة الحرارة لحد 100°C لتسريع المعالجة. هذا البحث يحدد ويحسن معايير معالجة البخار لإنتاج اعمده الإمداد كهربائية مسبقة الصب والاجهاد في شركه سودانيه. تتضمن هذه العوامل فترة تأخير بعد الصب (DT) من 0،1 ، 2 ، 3 ، 4 و 6 ساعات ، درجة حرارة معالجة قصوى (T) من 50 ، 60 و 70 درجة مئوية للحفاظ على فترة علاج معينة (CT) من 2 ، 3 ، 4 و 5 ساعات لتحقيق هذا الهدف ، تم إجراء العديد من التجارب المعملية لقياس مقاومة الانضغاط الخرسانيه بالمعالجة المذكورة أعلاه والتي تقارن بقيم العينات الخاضعة لطريقة معالجة المياه التقليدية. ثم تم استخدام منهجية (تاقوشي) لتحديد DT = 3hrs، CT = 4hrs و T = 70°C كنظام معالجة مثالي و DT أكثر فعالية. علاوة على ذلك ، تم اختبار العينات التي تم علاجها في هذه الدورة المثلى من أجل قوة الانثناء ومتانة الأداء (كبريتات وكلوريد لفترات تصل إلى 12 شهراً) ومقارنة مع تلك المعالجة بالماء. أظهرت النتائج أن المعالجة بالبخار توفر أداء أفضل في 3 أيام لقوة الانثناء ومتانة طويلة الأمد أو مشابهة للخرسانة بالمقارنة مع معالجة المياه.

الكلمات المفتاحيه: *دورة معالجة البخار ، تأخير الوقت ، علاج الوقت ، معالجة درجات الحرارة ، طريقة تاقوشي ، نفاذية الكلوريد ، هجوم الكبريتات*

ABSTRACT

Concrete steam curing under atmospheric pressure provides moisture and increases the temperature up to 100°C for accelerating the curing process. This research identifies and optimizes steam curing parameters for producing precast electrical poles in a Sudanese industrial entity. These parameters include a delay period after casting (DT) of 0, 2, 3, 4 & 6 hours, a maximum curing temperatures (T) of 50, 60 &70°C maintained for a specific curing period (CT) of 2, 3, 4 and 5 hrs. To attain this aim, several laboratory experiments have been carried out to measure compressive strengths after 7 days of the above curing regimes that are compared to values of specimens subjected to conventional water curing method. Then Taguchi methodology has been utilized to identify DT=3hrs, CT= 4hrs and T= 70°C as the optimum curing regime and DT as the most effective parameter. Furthermore, specimens cured under this optimum cycle have further tested for flexural strength and durability performance (sulphate and chloride ingress for periods up to 12 months) and compared with water-cured ones. The results show that the steam-curing provides better performance at 3 days for flexural strength and similar or superior long-term durability of concrete compared for water-curing.

Keywords: *steam curing cycle, delaying time, curing time, curing temperatures, Taguchi Method, chloride permeability, sulphate attack*

1 Introduction

Steam curing at atmospheric pressure is one of the techniques for obtaining high early strengths in concrete especially in precast concrete production. This technique enables early removal of shuttering and facilitates early vacating of the pre-stressing bed in precast industry providing a major economic advantage as well. This technique is used currently by the Sudanese Electricity Distribution Company (SEDC) to produce the electricity concrete poles. The strength enhancement depends on steam curing cycle.

The objectives of this study is to:

(1) Optimize the steam curing cycle for conventional concrete. For this purpose, a concrete mixture of C40 grade with water/cement ratio 0.45 will be designed and subjected to 3 variable parameters (i.e.) delay (DT) period before curing (0 to 6 hours), curing period (CT) in range between (2 to 5 hours) at three different maximum curing temperature (T) of (50, 60 and 70ºC).

(2) The compressive strength results of above condition will be compared with cubes subjected to the conventional water curing method measured at 7 and 28 days.

Then the optimum steam curing cycle will be compared with water curing by further testing for flexural strength and durability performance, namely sulphate and chloride attacks which will take a minimum duration of 12 months and 28 days respectively. The testing of the sulphate and chloride is meant to simulate harsh condition of burying the electrical pole in a soil with high concentration of these minerals, e.g. Port Sudan.

Many researchers have investigated the three parameters of steam curing cycle (T, DT & CT) to optimise the steam curing cycle for conventional concrete. For example, Deogekar *et al.* [1] investigated the influence of the three variable parameters of DT= (2 and 4 hours), C (6 and 8 hours) and T= (50, 60 and 70ºC). The compressive strength of these cubes was measured at 1, 7 and 28 days and compared with cubes subjected to the conventional water curing method. Also, the effects of each of the three parameters involved in the steam curing were analysed. From their results, it is observed that the optimum cycle is having a DT=4 hours, CT= 8 hours at a T of 60^0C. An attempt was also made to understand the vital parameters that affect the compressive strength significantly using Robust Design Engineering, alternatively known as Taguchi methodology.

In 1962, Merritt and Johnson [2] investigated the steam curing of Portland cement concrete at atmospheric pressure. They determined some of the relationships between the development of concrete strength and various parameters of the steam curing procedure. They studied DT= (2 and 6 hours), CT= (18, 42, and 66 hours) and T= (37, 50, 65 ,80 and 93ºC). They found that effect of DT for few hours get better strength than immediately curing. They found also that higher T requires longer DT. Their optimum steam curing cycle was T= 65^0C at a DT=3 hours. Their highest results were obtained at 65^0C and a DT= 6 hours.

Ramezanianpour *et al.* [3] investigated the effect of 36 steam curing cycles regimes on strength and durability of self-compaction concrete (SCC). They found that an increase in the DT leads to lowering of immediate compressive strength, whereas an increase in the T value leads to higher immediate compressive strength. Their durability tests demonstrated that application of steam curing cycle at T= 70^0C had negative effect on durability of SCC. This is attributed to rapid formation of C-S-H gel that produces heterogeneous and coarser pores structure. They concluded that the optimum curing cycle technically and economically wise is at T= 60^0C with a DT=3 hours and CT + cooling time=10 hours, whereas the cooling time is 2 hrs.

2 Materials and methods:

2.1 Material and mix proportion:

In this research ordinary Portland cement produced by *Alshemal* brand (MASS) has been used. Its initial and final setting times were 2.5 hours and 4 hours respectively. A crushed stone from (*Jabl Toriya*) with a maximum size =20mm, conforming to BS882-1992, water absorption=2% and a specific gravity=2.8 is used as a coarse aggregate. River sand from (Nile river state) conforming to BS882-1992 with absorption=3.1%, 39.4% passing 0.6mm sieve, and a specific gravity=2.6 is used as a fine aggregate.

According to the results of tests on raw materials, DoE mix design procedure [4] is used to design in the following limiting values:

1-Slump should ≤30 mm due to centrifugal compaction used to form hollow cylindrical electrical poles.

2- Two hours stripping strength after steam curing period should be ≥20N/mm^2 to meet requirement for de-stressing and handling.

3- 7 days compressive strength (store in air) should be ≥ 30 N/mm^2

4- 28 days compressive strength (store in air) should be ≥40 N/mm^2.

The mix proportion used to manufacture the poles without any admixture are 450Kg cement, 740Kg sand, 1030Kg coarse aggregates and 220KG water (including aggregate absorption water).

2.2 Curing regimes

2.2.1 Steam curing

The steam curing was applied using an automatic controlled cabinet of steam temperature with timing control of steam curing period. The cabinet has a steam generator capable of generating steam in different types of temperature by feeding pure water at a fixed rate of heat and cooling temperature of 90^0C/hr.

Delaying time (DT):

DT is defined as an initial delay prior to steaming in which concrete specimens are left for a predetermined delay periods of time, namely in this study: 0, 1, 2, 3, 4, and 6 hours.

Curing Time (CT)

CT is defined as a period of holding the maximum temperature constant or "holding time included heating and cooling time."

Based on the literature the experiments investigations were carried out for curing time for four curing periods 2,3, 4, and 5 hours.

Curing Temperatures (T):

T is defined as a target temperature to which the sample specimen is raised and held constant during the CT. Based on the literature; the experiments in this study have been carried out for 50, 60 and 70^0C

2.2.2 Water curing:

In this study, samples were left in a fog cabinet with relative humidity≥95% for 24 hours, then immersed in a water tank having temperature of 25^0C to be considered as reference samples and compared to steam-cured specimens. These specimens were tested at ages of 12 hrs, 3 days, 7 days and 28 days.

2.3 Methods and Apparatus:

2.3.1 Methods:

2.3.1.1 Compressive strength

After mixing concrete in a laboratory mixer and temperature of 25^0C, then slump test was measured and found to be 30mm +/-(10mm). Six cubes were cast for each cycle to be tested at 7 and 28 days. In total, 72*6= 432.cubes were cast to cover all steam curing cycles (delay time, curing time, curing temperature), plus extra 30 cubes for measuring stripping strength and 12 cubes for water curing. The steam cured specimens were stored in air until testing time at 7 or 28 days using 3 cubes for each day. The compressive test was carried out using a standard machine and the average of three cubes was calculated.

Then results of the aforementioned steam curing cycles have been analysed using Taguchi engineering method [5]. This method is used to identify optimum steam cycle that have produced the optimum highest 7days compressive strength. Then further samples were cast for the identified optimum curing regime for flexural strength (Section 2.3.1.2) and sulphate attack (Section 2.3.1.3) and rapid chloride permeability test (Section 2.3.1.4) and compared to the performance of reference water-cured specimens.

2.3.1.2 Flexural strength:

Twelve beams (75 cm * 15cm *15 cm) were cast and cured in water and the identified optimum steam curing cycle. Then the flexural strength was measured as per ASTM C78 [6] at ages of 2hours, 3days, 7days, and 28 days

2.3.1.3 Sulphate attack test:

The current ASTM C1012 (2004) ref [7] test method accelerates the sulphate attack mechanism by using a solution with a Na_2SO_4 concentration of 5% in which concrete cubes are immersed. This test requires measurement of cubes dimensions at several intervals up to 12 months. The measurement of dimensions was carried out by means of a digital micrometre. All cubes had initial dimensions of (150*150*150 mm) before the start of testing. Also the compressive strengths of specimens were measured.

2.3.1.4 Rapid Chloride Permeability Test (RCPT)

RCPT as per ASTM C1202 is a concrete chloride ion electric flux test that provides an important indicator for the durability of concrete. The ability of concrete to resist chloride ion penetration properties (density) is measured by a test indicator represented by six-hour power flux (in Coulomb) for the concrete specimens. This test is quick to evaluate the concrete resistance to the chloride ingress.

Six cylinders of 10 cm diameter and 20cm heights were cast for each type of curing (optimum steam cycle and water curing). The specimens were DE moulded, cured and then cut using the diamond saw to reduce the height to 5cm. Then they were fit in the RCPT cell and vacuum saturated with deionised water for 22 hours, tested at 7 and 28 days.

3. Results, Optimization and Discussion

3.1 Compressive strength:

The average compressive strength of 3 cubes cured in water tested for each age is depicted in Figure 1.

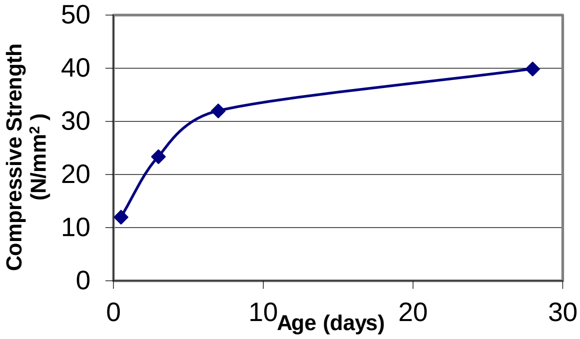

Figure 1: Average compressive strength at different ages of water-cured reference concrete specimens.

The 7 days strength is 32 N/mm^2, and 28days is 40N/mm2. The influence of the three steam curing parameters on the 7 days average

compressive strengths at different steam curing cycles are shown in Figure 2 and Figure 3. It is observed that the peak strength for T=50 and 60 are obtained for DT between 3 & 4hrs, while for T= 70, the peak is between DT= 4 and 6 hrs. All strengths for DT below the initial setting time of the cement used, i.e. 2.5hrs are lower than the peak with the minimum at DT=0. This agrees well with the ref [8] that before initial setting time the microstructure is fragile and affected by shrinkage.

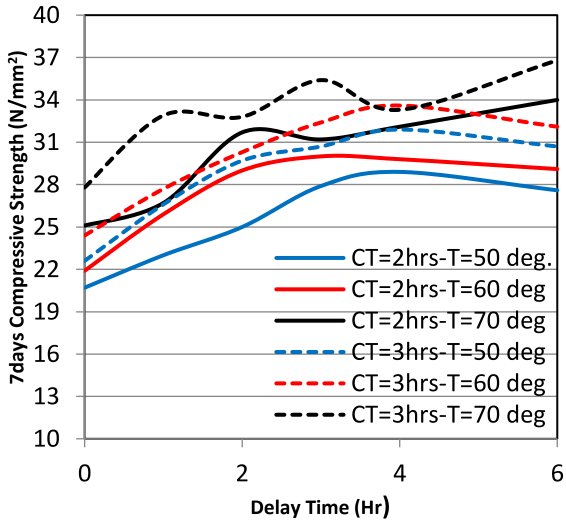

Figure 2: Effect of steam curing parameters (DT=0, 1, 2, 3, 4 and 5hrs, CT=2 and 3hrs , T=50, 60 and 70oC) on 7days compressive strength.

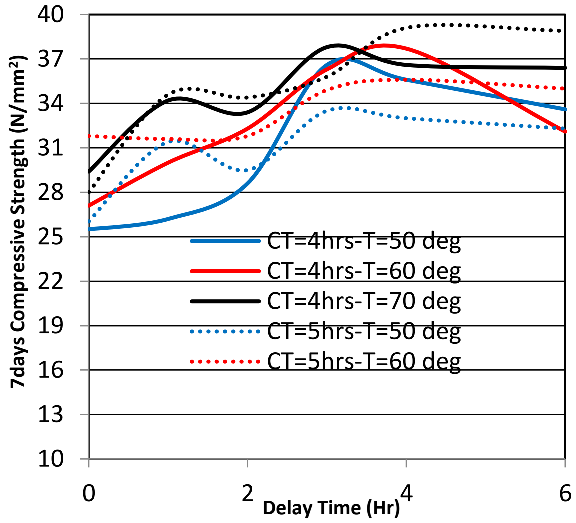

Figure 3: Effect of steam curing parameters (DT=0, 1, 2, 3, 4 and 5hrs, CT=2 and 3hrs , T=50, 60 and 70oC) on 7days compressive strength

3.2 Optimization:

3.2.1Taguchi design engineering method:

For optimizing results, Taguchi Robust Design Engineering methodology [9][5] has been used as a tool to identify the parameter that influences the compressive strength significantly relative to the other parameters considered in the study.

3.2.2 Identification of parameter affecting the compressive strength after 7 days using steam curing significantly:

The average of the 7days compressive strength of the steam cured for all 72 cycle samples was determined to be 31.1N/mm^2.

By taking the following factors to represent the effect of every variable where Fa represents effect of curing temperature (T), Fb represents effect of delay time (DT) and Fc represents effect of curing time (CT).

Effect of curing temperature (T):

Fa_1 represents the factor effect of temperature (T=50) corresponding to 50°C regardless of other two parameters values. It is calculated as the average strength of cubes having steam curing temperature 50°C at 7 days by neglecting the other two parameters (i.e. DT& CT) as follows:

1)Fa_1(50°C)=(20.7+23+25+27.8+28.9+27.6+22.6+26.6 +29.7+30.7+31.9+30.7+25.5+26.2+28.6+36.6+35.6+33 .6+25.8+31.1+29. 5+33.5+33+32.3)/24 = 29 N/mm^2

Similarly, for 60°C and 70°C

Fa_2(60°C) = 30.95N/mm^2 and Fa_3(70°C) =33.2 N/mm^2

Effect of delay time (DT):

Fb_0 represent the factor effect of DT corresponding to zero hrs. It is calculated as the average strength of cubes after 7 days having delay period zero hrs. By varying the other 2 parameters.

Fb_0=(20.7+22.6+25.5+25.8+21.9+24.4+27+31.4+25.1+ 27.8+29.4+28)/12=25N/mm^2

Similarly, Fb_1(1hrs.delay)=29.2N/mm^2, Fb_2=30.7N/mm^2, Fb_3=33.5N/mm^2, Fb_4=33.9 N/mm^2 and Fb_6= 33.2 N/mm^2

Effect of curing time (CT):

Fc_2 represent the factor effect of steam curing period corresponding to 2 hrs and is calculated as the average strength of cubes after 7 days having steam CTs of (2, 3, 4 and 5hrs) by varying other 2 parameters.

Fc_2 (2 hrs. steam curing period) = 27.6N/mm^2, Fc_3=30.5N/mm^2,Fc_4=32.7N/mm^2.and.Fc_5=33.2N/mm^2.

Now by considering differences between the factor effect for each parameter value and the average strength of 72 cycles denoted as μ= 31N/mm^2: as shown in **Table 1**.

By using ANOVA (analysis of variance) method: A1= $a_1^2+ a_2^2+ a_3^2$= 8.8%, B_1= b_0^2+ b1²+ b_2+ $b_3^2+ b_4^2+ b_6^2$= 52.4% and C_1= $c_2^2+ c_3^2 + c_4^2+ c_5^2$=19.54%.

Here A_1 is representative of the deviation in compressive strength after 7days obtained by changing the parameter value of temperature by 10ºC. Then the F ratio defined as weighted %age of effect of a parameter on the compressive strength, e.g. for temperature parameter (T), the F is calculated as follows:

(24*8.8/(24*8.8+12*52.3+18*19.54))*100= 17.7% , where 24 are of cycles having constant T, e.g. 50, 12 are cycles having constant DT, e.g. = 2hrs, and 18 are cycles having constant CT, e.g. =4hrs.

Similarly, for DT, F=52.7% and for steam CT: the F=29.54%.

Based on the results obtained using the Robust Design Engineering Methodology, it is inferred that the effect of DT is **(52.7%)** more significant compared to T **(17.7 %)** and CT **(29.54%).**

From experiments results in this research, besides the limitations for strength there are extra limitations on productivity time imposed by production department as follows:

The steam curing cycle total time should not more than 9 hours. It is worth noting that the cycle includes DT+ CT+ de-moulding and de-stressing time. The de-moulding and stressing time is estimated by the production team for a typical steam chamber containing 18 poles to about 100minutes, i.e. about 5 minutes for each pole.

Table 1: Difference between effect of each factor and average strength of all steam curing cycle

Parameter	Difference
a_1	Fa_1(50 ºC)-μ=29-31= -2
a_2	Fa_2(60 ºC)-μ=30.95-31= -0.05
a_3	Fa_3(70 ºC)-μ=33.2-31=2.2
b_0	Fb_0-μ=25.6-31=-5.4
b_1	Fb_1-μ=29.2-31=-1.8
b_2	Fb_2-μ=30.7-31=-0.32
b_3	Fb_3-μ=33.6-31=2.58
b_4	Fb_4-μ=33.9-31=2.88
b_6	Fb_6-μ=33.2-31=2.18
c_2	Fc_2-μ=27.6-31=-3.4
c_3	Fc_3-μ=30.5-31=-0.5
c_4	Fc_4-μ=32.7-31=1.7
c_5	Fc_5-μ=33.2-31=2.2

This means the constraints for DT+CT should be about 7 hrs. Given that from Figures 2 & 3 that the DT should be between 3 & 4hrs, this means the CT should be between 4 & 3hrs.

To identify the optimum cycle, Fa, Fb and Fc values obtained from Taguchi method are examined and parameters that fulfil the minimum strength of 30N/mm^2 and water –cured strength of 32N/mm^2 are identified. They are Fa_3 (70ºC)=33.2, i.e. = 70ºC and (Fb_3, Fb_4 and Fb_6) for DT =3, 4 & 6hrs respectively and (Fc_4 & Fc_5) for CT= 4 & 5hrs respectively. Therefore, the optimum steam curing cycle should have C= 70ºC, DT = 3 or 4hrs and CT= 4 or 5 hrs. To fulfil the condition of DT+CT=7hrs, the CT=5hrs and DT=4hrs should be ruled out, leaving DT=3hrs as the only option for CT is 7-3= 4hrs.

For this identified optimum steam cycle, it is important to verify that the 2hrs stripping strength should be

≥20N/mm². Therefore, a set of 12 cubes were cast, cured and crushed at ages of 2hrs after CT, 3days, 7 days and 28days. The strength values are 20, 30.5, 37.8 and 42N/mm², fulfilling all engineering and operational requirements. Also further specimens were cast for flexural strength, sulphate attack and chloride permeability.

3.3 Results and discussion of flexural and durability tests:

Figure 4 shows the flexural strength of the specimens cured in the optimum steam curing and water. The steam cured specimen provided higher strength up to 3 days while the water cured specimen surpassed the steam cured afterwards. This may be due to the introduction of microcracks in steam cured and the continuation of hydration with higher rate in the water-cured specimen.

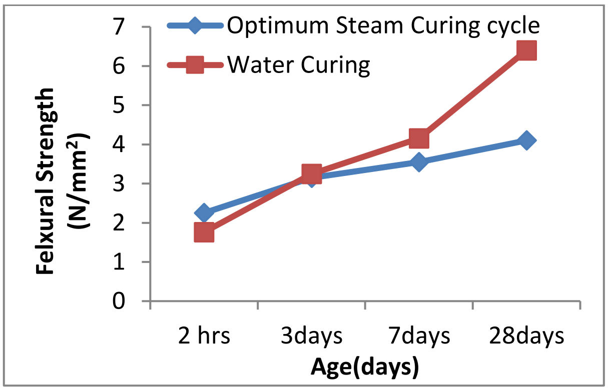

Figure 4: Comparison between Flexural Strength of the Optimum steam curing cycle and Water curing.

Figure 5 compares between performance of steam cured and water-cured specimens in RCPT. It shows that at 28 days the performance of the steam-cured is superior to the water-cured specimens.

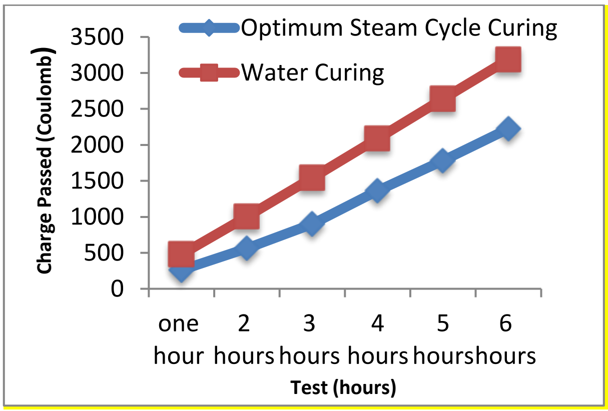

Figure 5: Chloride Permeability of the Optimum Steam Cycle-Curing and Water Curing specimens after 28 days.

Figures 6 &7 compare the compressive strength and expansion volumetric strain for water-cured and steam-cured specimens, respectively. Both Figures show remarkable differences in early ages up to 12 weeks but could be ultimately considered equivalent to each other. The significant observed expansion in the steam cured specimens in early ages could be attributed to delayed ettringite (AFt) formation, as it has been reported [10] that as curing temperature approaches 70°C, it may lower the solubility of gypsum, thus preventing the early formation of AFt.

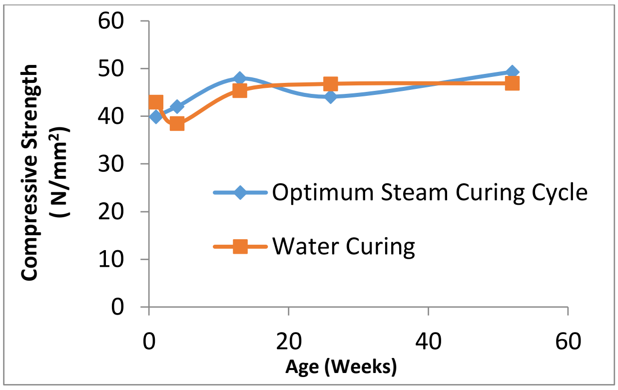

Figure 6: Compressive strength of cubes immersed in Na_2SO_4 (5%solution) up to 52 weeks of the Optimum Steam cycle and Water Curing specimens.

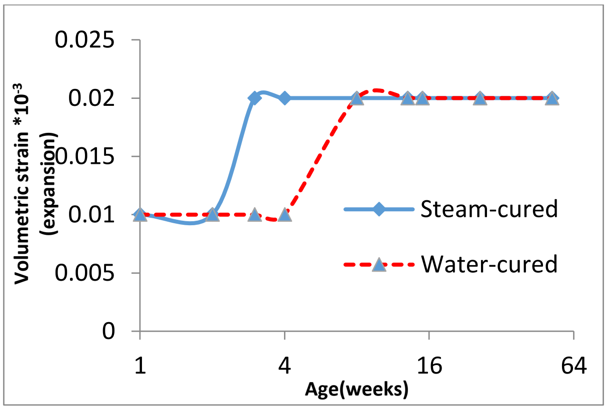

Figure 7: Comparison between Optimum Steam Curing cycle and Water Curing for volumetric expansion strain after immersion in Na_2SO_4 (5% solution) for duration up to 52 weeks.

4 Conclusions:

The results obtained from experimental studies can be summarized as follows:-

1. By using Robust Design Engineering (Taguchi) methodology it has been found that the effect of delaying time (DT) is the most significant on compressive strength compared to steam curing period (CT) and curing temperature (T).

2. The optimum steam curing cycle for strength and productivity requirement in the factory have been found to be T= 70ºC, DT= 3hrs and CT = 4hrs.
3. When specimens cured in the optimum steam curing cycle are compared with water-cured ones, they have been found to be superior in flexural strength up to 3days. They are also superior in resisting chloride ingress and ultimately after one year has almost similar strength and volume expansion strain in sulphate-rich environment.

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