Coventry University and
The University of Wisconsin Milwaukee Centre for By-products Utilization,
Second International Conference on Sustainable Construction Materials and Technologies
June 28 - June 30, 2010, Università Politecnica delle Marche, Ancona, Italy.
Main Proceedings ed. J Zachar, P Claisse, T R Naik, E Ganjian. ISBN 978-1-4507-1490-7
http://www.claisse.info/Proceedings.htm

Effectiveness of Different Solutions to Reduce Plastic Shrinkage in Hot Climate Concreting

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ABSTRACT

Hot climate concreting requires that some practices are used to reduce the undesirable effects caused by excessive water evaporation from the concrete surface, which tends to induce plastic shrinkage cracking and thereby reduce durability. This research highlights the effectiveness of different solutions to reduce plastic shrinkage: curing agent, cold water and cover with plastic sheet. Two levels fractional factorial array experimental design was used to reduce the number of tests, and allowed studying both the effect of different factors and interaction between factors. The measured parameters include: plastic shrinkage crack in 10 x 10 x 40 cm specimens, and compressive strength and rate of evaporation. A climatic chamber was used to simulate the hot climate. The results indicate that to minimize the plastic shrinkage the most adequate solution is the application of curing compound followed by the use of a plastic sheet cover. The most effective solution to decrease the evaporation is a plastic film sheet cover.

INTRODUCTION

Hot climate concreting is when the concrete is mixed, placed and cured at any combination of the following conditions: high ambient temperature, high concrete temperature, low relative humidity, wind velocity and solar radiation. The potential problems for concrete in the freshly mixed concrete state are: increased water demand, increased rate of slump loss corresponding tendency to add water at the jobsite, increased rate of setting (resulting in greater difficulty with handling, compacting finishing and a greater risk of cold joints), increased tendency for plastic shrinkage cracking and increased difficulty in controlling entrained air control. The potential problems for concrete in the hardened state may include: decreased 28-day and later strengths resulting from either water demand and/or higher concrete temperature, decreased durability resulting from cracking, increased potential for reinforcing steel corrosion (this is primary due to increased cracking) and increased permeability [Adam 2000; ACI 305]. On the other hand, fiber-reinforcement virtually eliminates plastic cracking. Plastic cracking can be effectively controlled by protecting the fresh concrete from drying as early as possible, but always before its surface dries out. Covering the concrete with plastic sheeting or spraying its surface with a suitable sealing compound are both adequate means to protect the concrete against plastic cracking.

Never previous research had investigated the effectiveness of this practices and the interaction between this practices. In this research the effectiveness of several practices, are investigated to avoid hot climate concreting problems mainly plastic shrinkage, strength decrease and evaporation rate. The investigated practices are: polypropylene fiber use, cure compound use, plastic film sheeting and cool water use.

There are many techniques to measure plastic shrinkage, include the use of rings [Weiss and Shah 2002]. One technique uses a small plate to measure free plastic shrinkage, with no embedment [Almusallam et al. 1998; Al-Amoudi et al. 2006; Bella et al. 2009]. A specific mold with embedding in bottom has also been used [Weiss and Olek 2003]; [Sivakumar and Santhanam 2007]. Other authors use specimens with a rigid notched substrate in order to measure restrained shrinkage [Banthia et al. 1996; Banthia et al. 2006]. In this paper a similar procedure to the last method was used.

Considering the great number of factors (solutions), two level fractional factorial array experimental design was used, which reduces considerably the number of tests, and permit the studying both the effect of different factors and the interaction between factors [Goupy 1996]. The total number of factors is six, four of these are principal (hot climate concreting solutions) and two are supplementary (environmental factors such as temperature and wind), the number of test is equal to 16 tests.

EXPERIMENTAL PROGRAM

Materials and mix proportions

The cements used in this study was CEM II/A. A crushed limestone sand (0-3mm) with specific gravity of 2.65, and aggregate (3-8 mm) with specific gravity of 2.65, the grading of there aggregates appear in Table 1.
Different admixtures were used; a plasticizer/water reducing agent (which conformed to NF EN 934-2) was utilized in all the concrete mixtures, a curing compound at watery phase was used at an amount of 200 g/m², some properties of the used plasticizer and curing compound are summarized Table 2.
A polypropylene fiber with surface agent (6mm length) was used with a dosage of 200 g/m^3, (Table 3).
The different used mixes for substrate base and overlay mortar are shown in Table 4.

Exposure and procedures

Substrate bases (Figure 1) with dimensions of 50×95×365 mm were cast using a specific mold to create a notched surface (Figure 1), the mixture proportions given in Table 4. Two 8 mm diameter rebar were used as reinforcement in the substrate bases to provide additional stiffness. On the day of the test, two identical specimens of the overlay to be investigated were prepared using the following procedures. A fully cured, air-dried substrate base was first placed in the

PVC mould measuring 100×100×400 mm. A 50 mm deep overlay with mixture proportions given in Table 1 was then poured over the substrate base and finished with a trowel. The overlay was either plain or fiber reinforced depending on the material being investigated. The substrate and the overlay 'assembly' were then transferred to an environmental chamber. A typical specimen with cracked overlay after demolding is shown in Figure 2. The specimen remained in the environmental chamber for an additional 23 hours after which the crack pattern developed in the overlay was characterized. For crack characterization, a magnification glass with accuracy of 0.01 mm was used. In addition to recording the maximum crack width observed in a given specimen, for each crack, the width was measured at several locations and averaged.

Table 1. Grading of Coarse and Fine Aggregates.

Sieve (mm)	% passing	Sieve (mm)	% passing
	Sand		Aggregate
4	100.00	10	100.00
2.5	94.75	8	100.00
1.25	56.75	6.3	95.62
0.630	32.25	5	73.44
0.315	19	4	47.56
0.250	16.25	3.15	22.56
0.160	10.25	2	2.87
0.080	4.25	1.25	1.31
Fillers	0.75	Fillers	0.06

Table 2. Admixtures and Curing Compound Properties.

Properties	Plasticizer	Curing compound
Specific gravity	1.185 ± 0.015	≈ 0.989
Appearance	Dark brown liquid	White liquid
PH (at 20 °C)	4.5 ± 1	≈ 5
Mass %	38.5 ± 1.9 %	
Chloride content	≤ 0.1	
Na_2O eq. content	≤ 2.0 %	

To simulate hot and dry climate curing in the lab, the 1800 mm x 1000 mm x 800 mm environmental chamber was used, and equipped with tow electrical heaters, electrical fan and thermo hygrometer, to regulating and monitoring the conditions inside. The temperature was maintained at 55 °C for the first 8 hours and 50 °C for 8 to 23 hours with the relative humidity (RH) of about 10% and the air velocity was 10 km/h.

The measured responses were: plastic shrinkage cracks measured a few hours after molding using a magnifying glass and cracks-meter, compressive strength of cub (100 x 100 x 100 mm^3) and water evaporation measured by continuous weighing (kg/m²/h).

Table 3. Polypropylene Fiber Properties.

specific gravity	0.90
Length	6 mm
Diameter	18 µm
Specific surface	250 m²/kg
Tensile strength	300, 400 MPa
Young's modulus	6000, 9000 MPa
Amount of fiber	180 million per m^3 of concrete

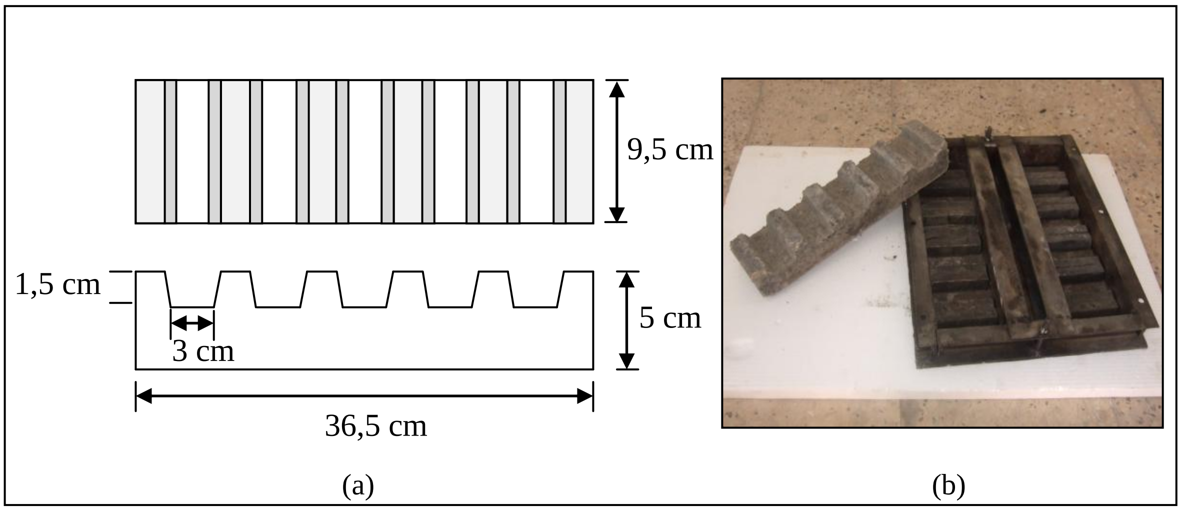

Fig. 1. (a) substrate dimensions, (b) finished substrate and using mold

Table 4. Mix Proportions

	Cement	Water	Sand	Aggregate	Superplasticizer	Compressive strength
	Kg/m^3					MPa
Substrate base	550	231	761.3	761.3	8.25	51.42
Overlay	1200	370	600	-	-	78.58

Fig. 2. A typical specimen with cracked overlay after demolding

Design of experiments

To study the efficiency of hot weather concreting solutions, which decrease cracking due to plastic shrinkage of mortar and high rate of evaporation, and improve strength; the design of experiment method (DEO) was used in order to reduce the number of tests and increase the number of studied factors, in this paper the total number of factors was six, an experimental design array was build with 6 factors, the number of tests of a full factorial design with two level per factor) is 64 tests ($N = 2^6$), but with DOE use the number of tests was limited to only 16 (in order to reduce materials consumption and save time) by the use of a fractional factorial design with $N = 2^{6-2}$.
Factors 1, 2, 3 and 4 represent hot climate concreting solutions, and they are principal factors. And factors 5 and 6 as environmental factors (temperature and wind), and they are secondary factors. Factor 5 (temperature) was defined equal to the third level interaction between factors 1, 2 and 3. And by the same manner factor 6 (wind speed) equal to the third level interaction between factors 2, 3 and 4. The experimental array is represented in the following Table 5.
To calculate the main effects for the different factors, in the case of full factorial design, the problem is easy, the main effect equal to the response vector multiplied by the factor effect, add all factors elements and divided by the number of tests in this case 16. But in fractional factorial design the problem is more complicate because the different main effects factors are aliased (5=123 and 6=234), then it's necessary to calculate the design generators of the design which are:

$5=123 \rightarrow \quad 5\times5=5\times123 \rightarrow \quad I=1235 \quad : 5^2=I$

$6=234 \rightarrow \quad 6\times6=6\times234 \rightarrow \quad I=2346 \quad : 6^2=I$

Therefore defining relation can be obtained as follows:

$1235\times2346=1456$

I=1235=2346=1456 (defining relation)

In order to determine the main effects of factor 1 and their aliases, we multiply both sides of the defining relation by '1'. This yields:

$1 \times I = 1 \times 1235 = 1 \times 2346 = 1 \times 1456$
$1 = 235 = 12346 = 456$, as $1^2 = I$

Table 5. Experimental Array

N° Test	factor 1 PS plastic Sheet	Factor 2 CC Curing compound	Factor 3 PF Polypropylene fiber	Factor 4 CW Cool water	Factor 5 T 5=1x2x3 Temperature	Factor 6 W 6=2x3x4 Wind velocity	Response
01	+1	-1	-1	+1	+1	+1	Y1
02	+1	+1	-1	+1	-1	-1	Y_2
03	+1	-1	-1	-1	+1	-1	Y_3
04	+1	+1	+1	-1	+1	-1	Y_4
05	-1	-1	+1	-1	+1	+1	Y_5
06	-1	-1	+1	+1	+1	-1	Y_6
07	-1	-1	-1	-1	-1	-1	Y_7
08	-1	+1	-1	+1	+1	-1	Y_8
09	+1	+1	+1	+1	+1	+1	Y_9
10	+1	-1	+1	+1	-1	-1	Y_{10}
11	-1	-1	-1	+1	-1	+1	Y_{11}
12	-1	+1	+1	-1	-1	-1	Y_{12}
13	-1	+1	+1	+1	-1	+1	Y_{13}
14	-1	+1	-1	-1	+1	+1	Y_{14}
15	+1	+1	-1	-1	-1	+1	Y_{15}
16	+1	-1	+1	-1	-1	+1	Y_{16}
Level-1	With out	0	0	25°C	45°C	10 km/h	
Level+1	With	200g/m²	$1200 g/m^3$	0°C	55°C	15 km/h	

Sign equal must be replaced by a sign plus, to estimate the main effect of factor 1 and their aliases:

$L_1 = 1 + 235 + 456 + 12346$

And all other main effects and their aliases can be estimated by the same manner:

$L_2 = 2 + 135 + 346 + 12456$
$L_3 = 3 + 125 + 246 + 13456$
$L_4 = 4 + 156 + 236 + 12346$
$L_5 = 5 + 123 + 146 + 23456$
$L_6 = 6 + 145 + 234 + 12356$

RESULTS AND DISCUSSION:

In DOE (Design Of Experiment) the experimental results can be displayed and analyzed by different methods, for that Pareto plot and main effects plot were used. The Pareto plot allows detecting the factor and interaction effects which are most important to the process or design optimization study has to deal with (Antony 2003). It displays the absolute values of the effects. A main effect plot is a plot of the mean response values at each level of a design parameter or process variable. One can use this plot to compare the relative strength of the effects of various factors.

The sign and magnitude of a main effect would tell us the following:

- The sign of the main effect tells us of the direction of the effect, i.e. if the average response value increases or decreases.
- The magnitude tells us of the strength of the effect.

Influence of different solutions and environmental conditions on plastic shrinkage

Figures 3, 4 and 5 show that the main effects CC (curing compound) and PS (plastic sheet cover) are judged to be statistically significant on reducing plastic shrinkage such as cracks width and crack length at early age. The figures show that cool water and polypropylene fiber use have insignificant effects on plastic shrinkage.

Cool water use gives an interesting effect when new substrates are used, probably because it's efficient in reducing hydration temperature. The most influent environmental factor on plastic shrinkage is the air velocity (wind) compared with temperature.

Influence of different solutions and environmental conditions on evaporation

In order to decrease the evaporation rate, Figures 6, 7 and 8; show that the most efficient solution at all time is the plastic sheet cover, and in the second comes the curing compound. The main effects of factors CW (cool water) and PF (polypropylene fiber) are considered statically not significant.

Influence of different solutions and environmental conditions on compressive strength in long term

An interesting result is shown in Figure 9, the most efficient solution to improve compressive strength in long term is cool water use, and all the other solutions such as PF (polypropylene fiber), PS (plastic sheet) and CC (cure compound) are statically not significant.

Figure 9 shows also that the compressive strength in long term decrease significantly when the air velocity is in high level, which can be explain by the increase of evaporation when the air velocity increase, furthermore the compressive strength in long term is improved when the temperature is in maximum level, that is explicate by the thermal activation of cement hydration.

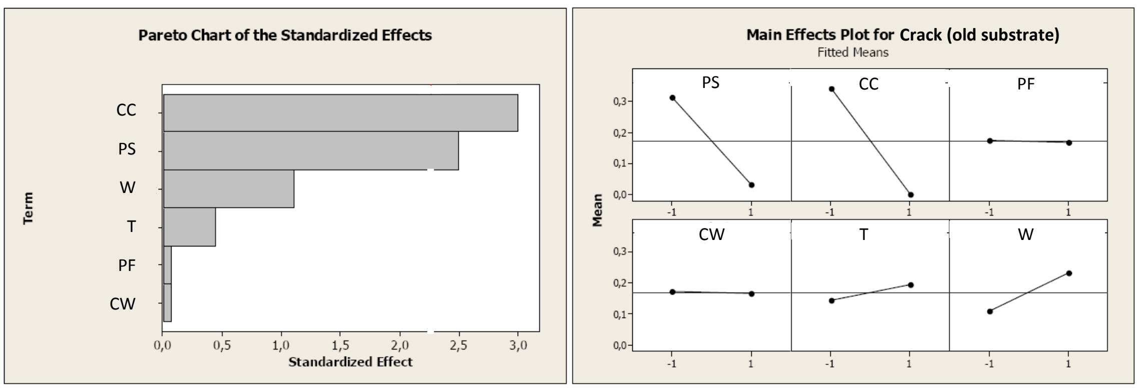

Fig. 3. Pareto effect of the standardized effects, and the main effect plot of different factors on cracks with old substrate

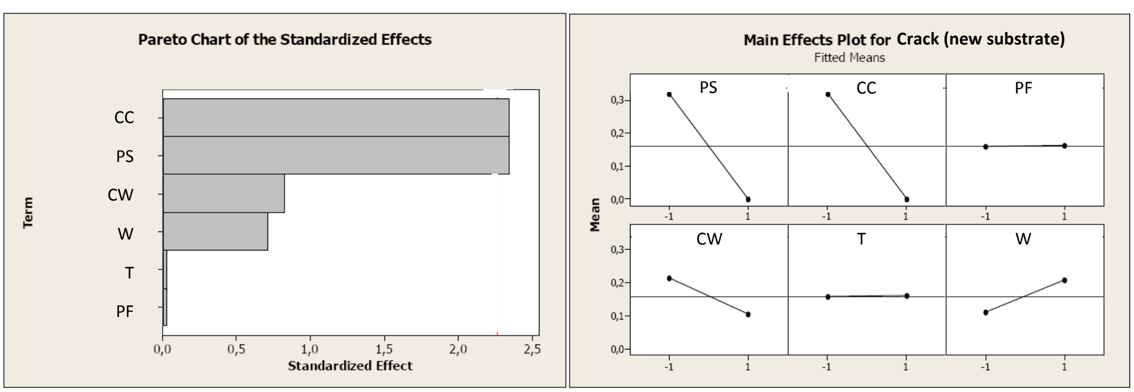

Fig. 4. Pareto effect of the standardized effects, and the main effect plot of different factors on cracks with new substrate

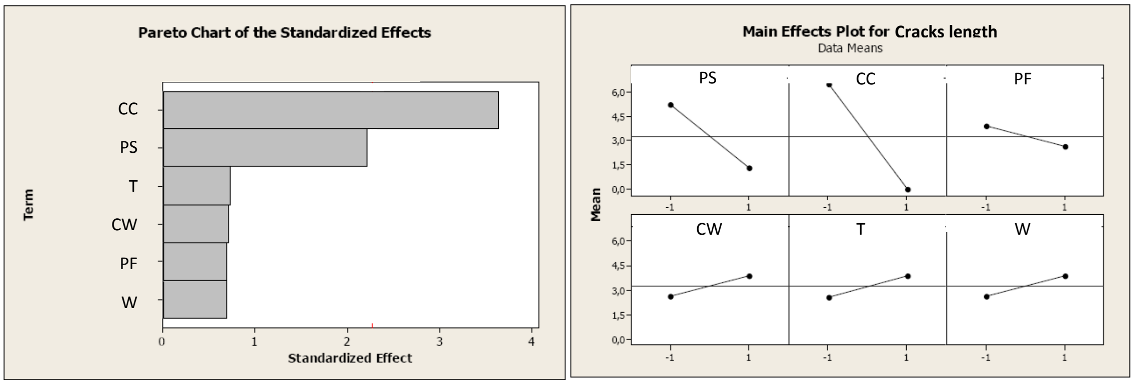

Fig. 5. Pareto effect of the standardized effects, and the main effect plot of different factors on cracks length

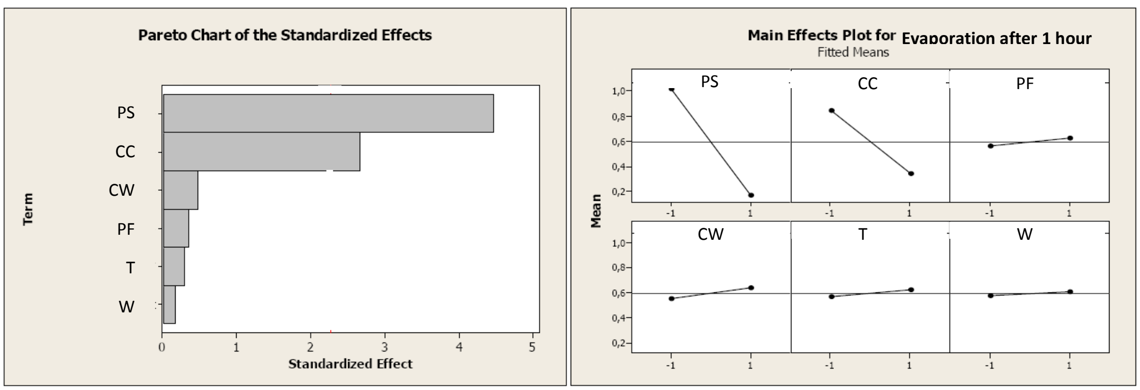

Fig. 6. Pareto effect of the standardized effects, and the main effect plot of different factors on evaporation after 1 hour

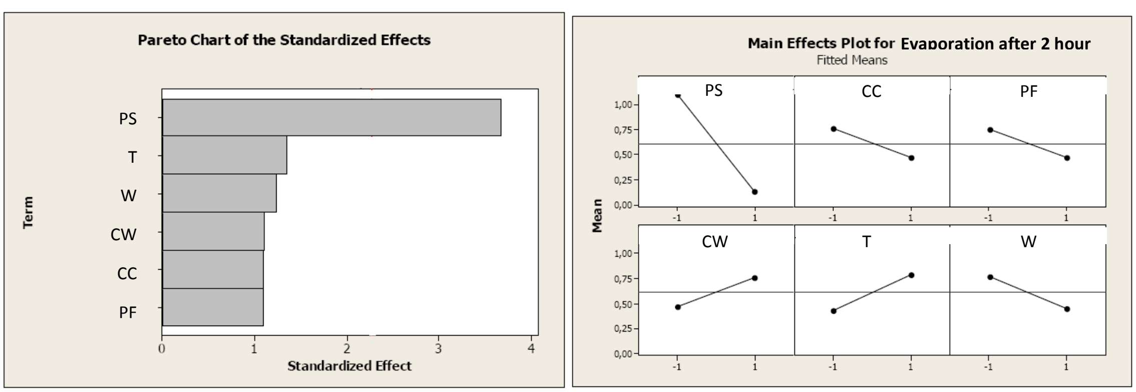

Fig. 7. Pareto effect of the standardized effects, and the main effect plot of different factors on evaporation after 2 hour

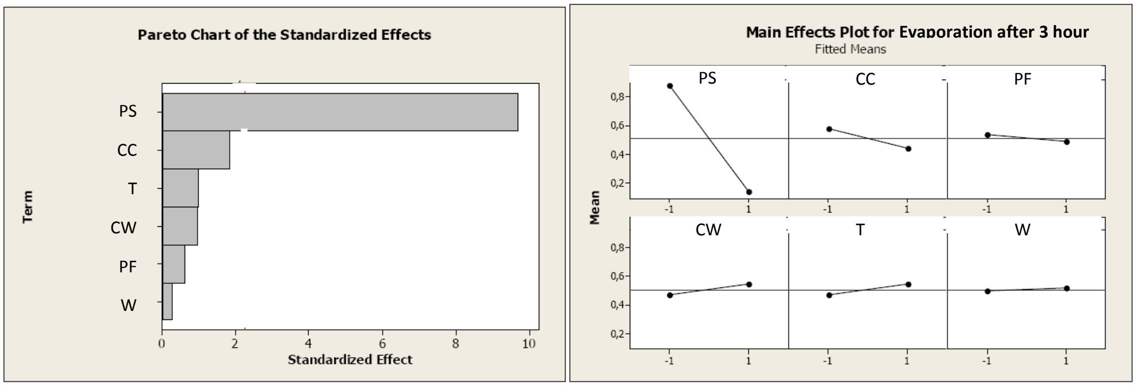

Fig. 8. Pareto effect of the standardized effects, and the main effect plot of different factors on evaporation after 3 hour

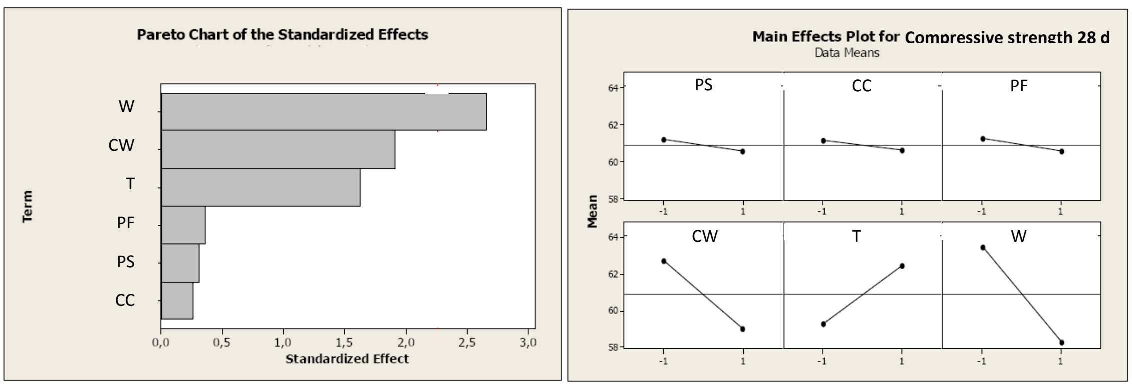

Fig. 9. Pareto effect of the standardized effects, and the main effect plot of different factors on compressive strength 28 at day

CONCLUSION

Based on the experimental program conducted and the data developed in this investigation, the following conclusions could be drawn:

- To reduce the restrained plastic shrinkage cracks width, ***curing compound*** and ***plastic sheet cover*** are both the most interesting solution.
- And ***curing compound*** gives the best results to reduce cracks' length.
- In order to minimize the rate of the evaporation, the use of ***plastic sheet cover*** is the very good solution.
- Concreting with ***cool water*** improves compressive strength at long term. And it didn't give good results in reducing evaporation by the decrease temperature of concrete, contrary to the ACI 305; but cool water use may regular the temperature of hydration and improves hydration products microstructure.

- ***Polypropylene fiber*** didn't give interesting results to decrease the restrained plastic shrinkage cracks, it's not as known before.
- The increasing of temperature with adequate hot climate concreting procedures, improve strength in long term.
- Finally, it's apparent that the coupling of cool water concreting and the use of plastic sheet cover or the curing compound may be the best solutions to reduce the restrained plastic shrinkage cracks and improve compressive strength at long term.

ACKNOWLEDGEMENTS

For his assistance in the lab Kadri Boufeldja is gratefully acknowledged. Admixtures, cure compound and polypropylene fiber were provided by Sika Aldjazair company, Billal Announ is gratefully acknowledged from R&D department of Sika Aldjazair.

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