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*Research Article*


## MASS CONCRETE CONSTRUCTION USING SELF-COMPACTING MORTAR


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**ABSTRACT**

Risk of thermal cracking is a well-known problem in mass concrete structures. One of the steps in mitigating this problem is to keep the initial placement temperature of concrete as low as possible. From this standpoint, Preplaced Aggregate Concrete (PAC) is advantageous because the friction among the coarse aggregate particles during the mixing operation causes the initial temperature of concrete to rise. Making PAC by the conventional method of grout injection requires special equipment and skilled workers. An alternative method using a self-compacting mortar for grouting preplaced aggregate was investigated in this study. Using different concrete compositions made with locally available cementitious materials and aggregate fractions, massive concrete cubes, each 1 m. were prepared. The specimens were tested for thermal and mechanical properties. In addition to low temperature rise that is suitable for mass concrete, the PAC method produced concrete specimens with compressive strength and modulus of elasticity values comparable to conventional concrete.



***Keywords:*** *Preplaced Aggregate Concrete, Mass Concrete, Self-compacting Concrete, High Volume Pozzolan, Heat of Hydration, Thermal Cracks*

## 1. INTRODUCTION

In massive structures, it is well known that the combination of heat produced by cement hydration and relatively poor heat dissipation conditions results in a large temperature rise in concrete within a few days after placement. Subsequent cooling of concrete to ambient temperature often causes cracking. A primary requirement in the design and construction of mass concrete structures is that the structure should remain a monolithic, free from cracks, therefore every effort to control the temperature rise is made through proper selection of materials, mix-proportions, curing conditions, and construction practice.

Precooling of fresh concrete is a commonly preferred method of minimizing the subsequent temperature drop. For this purpose, chilled aggregates and/or ice shavings are often specified for making concrete mixtures. During the mixing operation, the latent heat needed for melting of ice is withdrawn from other components of the concrete mixture, providing a very effective way to lower the temperature (Mehta and Monteiro, 2005).

The temperature of freshly placed concrete at a given time depends on the placement temperature and the amount of temperature rise subsequent to placement. The temperature rise that occurs after the placement is controlled by the heat of cement hydration. Thus, the first step to be taken to control the temperature rise is the selection of a cementitious material with low heat of hydration. For this purpose, use of high volume of pozzolans is an effective way to prevent thermal cracks. When this is not adequate, a network of pipes is installed in the formwork before the concrete placement, so that cooled water may be circulated later in this pipe network. Some of the heat generated as a result of hydration is thus removed and excessive rise of concrete temperature is avoided. This procedure, called post cooling, is effective in controlling the risk of thermal cracking, but it is quite cumbersome and costly (ACI Committee 207, 2008).

Preplaced Aggregate Concrete (PAC) is defined as the concrete produced by placing coarse aggregate in a form and later injecting a cement-sand grout to fill the voids (ACI Committee 116, 2008). PAC technology was first used in 1937 by Louis S. Wertz and Lee Turzillo during rehabilitation of Santa Fe railroad tunnel near Martinez, California. They were grouting the voids in the concrete at crown areas. In order to reduce the consumption of grout, they thought of filling most of the spaces in formwork with coarse aggregate, before the grouting operation. The resulting concrete showed good performance and attracted the attention of other researchers. Professor Raymond E. Davis, from University of California at Berkeley, developed grout mixtures and basic procedures to make this new method more widely applicable. As a result of his studies, he determined many of the unique properties of PAC, which is also known as two-stage concrete (ACI Committee 304, 2008). Since a large volume of the two-stage concrete is occupied by coarse aggregate, it is likely that variations in coarse aggregate content will significantly influence the strength of PAC (Abdelgader, 1996). Because of this, the commonly used formulae for compressive strength of traditional concrete are not valid for PAC (Rajabi and Moaf, 2017). Although the modulus of elasticity can be satisfactorily predicted from the compressive strength value for normal concrete, there is no background information for the evaluation of elastic modulus in the case of PAC (Abdelgader and Górski, 2002). However, there are some equations in the literature offered for PAC to derive the static modulus of elasticity as a function of the compressive strength (Abdelgader and Górski, 2003). Similarly, the equations used for ordinary concrete to predict the tensile strength (splitting) from the compressive strength value are not applicable for PAC, but there are some relations between the tensile strength and the compressive strength of PAC offered in the literature (Abdelgader and Ben-zeitun, 2004; Abdelgader and Elgalhud, 2008). Good quality PAC grout can be prepared in high-speed mixers and because of the unique equipment involved, PAC technology is underutilized. However, there are some grout mix designs which can be followed to achieve similar results by using conventional mixing equipment and recently developed super-plasticizing admixtures (Nowek *et al*., 2007).

In this study, the authors assumed that application of PAC method in combination with the use of high volume pozzolan could eliminate the need for the cumbersome and costly post cooling operation for mass concrete construction. Making PAC by the conventional grout injection method requires special equipment and skilled workers. An alternative method, using a self-compacting mortar for grouting was investigated in this study. Four concrete cube specimens, each 1 m in volume and having different mix designs, were cast; three cubes by PAC method with the new approach based on the use of self-compacting grout, and one cube as conventional concrete for reference purposes.

## 2. EXPERIMENTAL STDUY

### 2.1. Materials

Four sizes of aggregate fractions, namely 0 - 3 mm, 7 - 15 mm, 15 - 30 mm and 30 - 60 mm, were used. They include both fine and coarse aggregates, from the same geological region (nearly equal content of monzonite-monzodiorite and meta-andesite minerals). The specific gravity, absorption capacity values, and sieve analyses results of aggregates are shown in Table 1 and Table 2, respectively.

Table 1. Specific Gravity and Absorption Capacity of the Aggregates

| Aggregate | Specific Gravity | | Absorption Capacity |
|---|---|---|---|
| Class, mm | Dry | SSD | (%) |
| 0-3 | 2.59 | 2.61 | 0.98 |
| 7-15 | 2.66 | 2.68 | 0.79 |
| 15-30 | 2.66 | 2.69 | 1.02 |
| 30-60 | 2.7 | 2.71 | 0.6 |

Table 2. Sieve Analysis of the Aggregates

| Sieve No. (mm) | % Passing 0-3 mm | 7-15 mm | 15-30 mm | 30-60 mm |
|---|---|---|---|---|
| 63.5 | 100 | 100 | 100 | 100 |
| 50.8 | 100 | 100 | 100 | 69.26 |
| 28.1 | 100 | 100 | 100 | 14.85 |
| 25.4 | 100 | 100 | 93.4 | 0 |
| 19.05 | 100 | 100 | 70.42 | 0 |
| 12.7 | 100 | 100 | 19.37 | 0 |
| 9.53 | 100 | 85.41 | 1.54 | 0 |
| 4.76 | 99.81 | 28.94 | 0 | 0 |
| 2.38 | 94.68 | 0 | 0 | 0 |
| 1.19 | 60.17 | 0 | 0 | 0 |
| 0.59 | 33.6 | 0 | 0 | 0 |
| 0.297 | 16.48 | 0 | 0 | 0 |
| 0.149 | 8.19 | 0 | 0 | 0 |

The same type of a Portland cement and a blended Portland cement, which are commercially available in Turkey were used in all concrete mixtures. The Portland cement is classified as CEM I 42.5 according to Turkish Standards (similar to Type I - Ordinary Portland Cement according to ASTM Standard C 150). The blended cement is classified as CEM II/B-P 32.5 according to TS EN 197-1 (similar to Portland-Pozzolan Cements according to ASTM Standard C 595), and contains about 35% (by weight) pozzolanic addition (EN TS 197-1, 2012; ASTM C 150, 2012; ASTM C 595, 2000).

The fly ash was obtained from a thermal power plant in Turkey, and it is similar to ASTM Class F fly ash, C 618 (ASTM C618-15, 2015). The brick powder was obtained from a factory in Manisa (Turkey), which collects the broken bricks from brick factories. It is well known that pieces of clay bricks were widely used in Roman and Byzantine structures to obtain hydraulic mortars. Crushed and/or powdered bricks were utilized for load-bearing and water-resistant purposes (Degryse *et al*., 2002; Moropolou et. al, 2000; Baronio and Binda, 1997). Recent studies have shown that ground clay brick when added to cement in sufficient amount increased the resistance of mortar against chemical attacks (Afshinnia and Poursaee, 2015; Kishar *et al*., 2013; Turanlı *et al*., 2003).

The PAC specimens are designated according to their dominant cementitious component, such as FA for Fly Ash, BP for Brick Powder, BC for Blended Cement, and CC for Conventional Concrete. The difference between the middle and the surface temperatures of the specimens was monitored by thermocouples located in the specimens until the temperatures reached a steady-state. Compressive strength and modulus of elasticity were determined from the core specimens taken at the ages of 28, 90, 180, 360, 540 and 720 days. Minimum three cores were tested at each age and the diameter of the cores were 250 mm.

The physical properties and the chemical analysis of all the cementitious materials used are given at Table 3 and Table 4, respectively. As chemical admixtures, the same superplasticizer and air-entraining admixture were used in all concrete mixtures**.**

Table 3. Physical Properties of the Cementitious Materials

| Property | | Portland Cement | Blended Cement | Fly Ash | Brick Powder |
|---|---|---|---|---|---|
| Specific Gravity | | 3.12 | 2.78 | 2.1 | 2.64 |
| Blaine Fineness ($m^2$/kg) | | 392 | 480 | 289 | 400 |
| W/C for NC | | 0.26 | 0.27 | 0.5 | - |
| 45 µm sieve residue (%) | | - | - | 27 | 37 |
| Strength Activity Index (%) | 7 days | - | - | 82 | 66.2 |
| | 28 days | - | - | 89 | 80.3 |
| Setting Time (min) | Initial | 108 | 110 | - | - |
| | Final | 162 | 165 | - | - |
| Compressive Strength (Mpa) | 3 days | 27.6 | 15.4 | - | - |
| | 7 days | 39 | 19.6 | - | - |
| | 28 days | 47.7 | 34.1 | - | - |
| | 90 days | - | 38.8 | - | - |
| Heat of Hydration (cal/g) | 3 days | 67.5 | 45.9 | - | - |
| | 7 days | 74.9 | 49 | - | - |
| | 28 days | 92.1 | 74 | - | - |
| | 90 days | - | 83.1 | - | - |

Table 4. Chemical Analysis of the Cementitious Materials

| % by weight | Portland Cement | Blended Cement | Fly Ash | Brick Powder |
|---|---|---|---|---|
| CaO | 62.56 | 41.93 | 3.34 | 3.94 |
| $SiO_2$ | 20.47 | 31.31 | 58.4 | 62.7 |
| $Al_2O_3$ | 5.68 | 8.94 | 18.8 | 17.1 |
| $Fe_2O_3$ | 3.08 | 4.19 | 10.6 | 6.84 |
| MgO | 1.8 | 3.23 | 4.52 | 2.25 |
| $SO_3$ | 3.22 | 2.09 | 1.75 | 0.84 |
| $K_2O$ | 0.95 | - | 1.86 | - |
| $Na_2O$ | 0.3 | - | 0.22 | - |
| $Cl^-$ | 0.014 | - | - | - |
| $P_2O_5$ | - | - | 0.25 | - |
| $Mn_2O_3$ | - | - | 0.22 | - |
| Free CaO | 0.98 | - | - | - |
| Loss on Ignition | 2.49 | 5.46 | 0.77 | 2.67 |

Table 5. Mixture Proportions

| | | Amount (kg/m$^3$) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Portland Cement | Blended Cement | Fly Ash | Brick Powder | Super-plasticizer | Air-entrainer | Water | Aggregate (mm) 0-3 | 7-15 | 15-30 | 30-60 |
| Specimen | CC | 115 | - | 173 | - | 2.88 | 0.576 | 144 | 538 | 365 | 457 | 465 |
| | FA | 115 | - | 173 | - | 5.76 | 0.576 | 144 | 576 | - | - | 1420 |
| | BP | 118 | - | - | 177 | 5.9 | 0.59 | 148 | 590 | - | - | 1420 |
| | BC | - | 175 | 113 | - | 5.76 | 0.576 | 144 | 576 | - | - | 1420 |

The mixture proportions of the four concrete types are shown in Table 5. The same coarse and fine aggregates gradations were used for all PAC specimens. As the volume of the preplaced coarse aggregate is determined by the volume of the formwork used, the same amount of aggregate was used for all specimens. The amount of fine aggregate was fixed as twice the amount of cementitious material, therefore, it differed in each concrete type due to the fact that the cementitious material required to fill the volume of voids differed according to its specific gravity. Note that all the specimens, including the reference specimen, contained 60% (by weight) mineral admixture. The gradation of the aggregate for the reference specimen was arranged to have a well-graded aggregate with a maximum aggregate size of 60 mm. The W/C ratio was kept the same (0.5) for all concrete types. Also, all the specimens contained 0.2% by mass of air-entraining admixture. While the superplasticizer content was 0.2% by mass for the PAC specimens, it was 1% by mass for the reference concrete in order to have 75 mm slump which is appropriate for filling all the voids within the preplaced aggregate.

## 2.2. Research Significance: A New Method for Making PAC

In the conventional method of making PAC, first the coarse aggregate is placed into the forms, and then the grout is injected through the pipes inserted in the coarse aggregate mass by special pumps, till the injected grout rises up to the top surface of the preplaced coarse aggregate mass. Despite the many advantages of making concrete by this way as compared to conventional concrete, in many situations this method requires special equipment and experienced workers. Self-compacting concrete (SCC) technology is a new and technique that was developed for placement of concrete mixtures especially where the closely-spaced reinforcement does not allow concrete compaction by vibration. In SCC, the rheology of concrete is improved by the use of new generation of superplasticizers and chemical admixtures such that the concrete mixture is very fluid but does not segregate (Demir *et al*., 2018; Akgüngör *et al*., 2017). It fills all the voids in the formwork without requiring any high-pressure injection or vibration. The authors used SCC for making PAC mixtures of this study. By using a suitable superplasticizer and a large volume of pozzolanic admixtures, the rheology of the mortar was controlled such that it could fill without segregation the voids when placed over the preplaced coarse aggregate. Thus, this method can be called as making PAC by a self-compacting grout (PAC-SCG).

This way of making PAC has been found to be much more advantageous compared to the conventional injection method, since it does not require any special equipment, such as pumps and insert pipes, or any skilled workers. The grout prepared by a conventional drum mixer, when placed at the top of the preplaced coarse aggregate, penetrates into voids by gravity. The question about this method was how can one be sure whether all the voids have been filled? This can be simply checked by the amount of grout consumed; because, if the volume of voids within the preplaced coarse aggregate mass is known, the amount of grout required to fill these voids can be determined easily before starting the operation. The volume of voids within a preplaced coarse aggregate can easily be determined by filling a container of known volume with that coarse aggregate gradation in SSD state, and then adding water to the container till it overflows. In such a test, it is obvious that the volume of the water consumed is equal to the volume of voids within the aggregate mass; and proportioning this volume to the volume of the container used for the test, the actual volume of voids can easily be calculated by using the volume surrounded by the formwork.

In this research, it has been observed that the amount of grout required to fill all the voids within the preplaced coarse aggregate mass, which had been determined before starting to place the grout, was totally consumed when the grout appeared at the top of the aggregate mass, which means that all the voids within the preplaced coarse aggregate mass have been completely filled. As a final check on the uniformity of the void-filling operation, concrete cores can be obtained and visually examined.
Photograph of a cross-section of the concrete core prepared by the new PAC-SCG method is shown in Fig. 1, and a similar photograph of concrete prepared by the conventional PAC method used for restoration of Barker Dam under the supervision of Professor Raymond E. Davis about 60 years ago, is shown in Fig. 2. When these photographs are compared, it is seen that the voids in the preplaced aggregates have successfully been filled by the SCG technique.

Fig. 1. A sample of PAC prepared by the new SCG method

Fig. 2. A sample of PAC prepared by the conventional method for the restoration of Barker Dam

### 2.3. Test Methods

All the concrete tests were carried out at the Materials of Construction Laboratory of the Civil Engineering Department of Middle East Technical University, Turkey, and in accordance with the ASTM Standard Test Methods.

Prevention of thermal cracking is an important goal in mass concrete construction, therefore large concrete samples are used to monitor temperature changes in the proposed mix design. During the preparation of the specimens, four thermocouples were placed in each specimen, two of them at the surface and two of them in the middle of the specimen, as shown by Fig. 3. The reason of using two thermocouples at the same location of the specimen was to insure the continuity of temperature measurement in case one of the thermocouples stopped working. Temperature measurements were discontinued when they reached a steady-state.

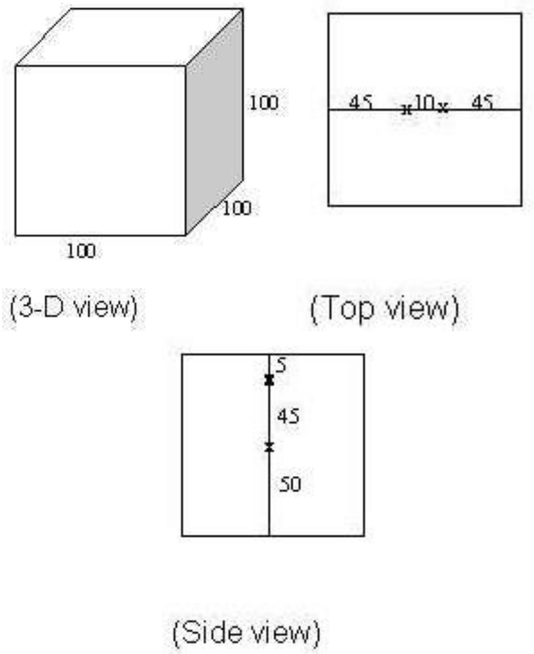



Fig. 3. The location of the thermocouples in the concrete cube specimens (the dimensions are given in cm)

Since it was not possible to carry such big specimens to the curing room of the laboratory, a special tent was built for these specimens, and they were kept in this tent till the formworks were removed. The formworks were removed after the task of monitoring the concrete temperatures had ended with the reaching of steady temperature values, which took approximately one to two weeks, depending on the type of the concrete mix. The ambient temperature and the relative humidity inside the tent were monitored by digital equipment, and an attempt was made to keep them as constant as possible.

When the concrete temperature reached a steady-state, the formwork was removed, and rate of strength development was monitored by taking core samples and testing them under compression at ages 28, 90, 180, 360, 540 and 720 days. Modulus of elasticity values were also determined for the same specimens.

## 3. RESULTS AND DISCUSSION

### 3.1. Temperature Measurements

The results of temperature measurement at the surface and middle of concrete specimens are shown in Fig. 4. It can be observed that the maximum peak temperature, 41 C, occurred in concrete CC, and the minimum, 37 C occurred in concrete BC. From standpoint of the risk of thermal cracking, the peak temperature difference is more important than the peak temperature itself (Mehta and Monteiro, 2005). The maximum peak temperature difference 11.5 C occurred in the case of concrete CC, which is acceptable for mass concrete; however, this is higher than the corresponding temperature difference of 9.5 C with specimen FA containing the same amount of total cementitious materials as concrete CC but using the new method.

The minimum peak temperature difference occurred with the specimens BP and BC, one of which contains brick powder, the other contains a natural pozzolanic mineral admixture. Fly ash is already known as a successful mineral admixture in reducing the heat of hydration, but this study shows that brick powder and interground fly ash in blended cements are also a very suitable for mass concrete due to their effectiveness in reducing the heat of hydration. It is interesting to note that the blended cement containing interground fly ash was more effective in reducing the heat of hydration than separately batched fly ash, the explanation of which requires further investigation.

While evaluating the specimens under the topic of temperature measurements, the other two important criteria are the rate of hydration heat evolution, which is represented by the time of occurrence of the peak temperature difference, and the length of the duration for the temperatures to get stabilized, which represents the rate of heat release of the specimen. Evaluating the specimens from these criteria points of view, the shortest duration for the temperatures to get stabilized has occurred with the specimen CC, which also showed the maximum peak temperature difference in minimum time. On the other hand, the longest durations were recorded for concrete specimens BP and BC which also showed minimum peak temperature differences with the slowest rates of heat release. As a result it can be concluded that, as the peak temperature increases (which means that as the amount of heat of hydration increases), the time required to reach this peak value decreases (which means that the rate of heat evolution increases), and the length of duration for the temperatures to get stabilized decreases. The time to reach the peak temperature value is important, because during the first few days following placement the rate of cooling or heat removal can be as high as possible since the elastic modulus of concrete is relatively low. The strength and the elastic modulus generally increase rapidly until after the peak in concrete temperature has been experienced. When concrete has become elastic, it is important to have temperature drop as slowly as possible (ACI Committee 207, 2008).

Photographs of cross-section of concrete specimens, both without and with magnification (1 to 25) are presented in Fig. 5 and Fig. 6, respectively. None of the specimens showed thermal cracking.

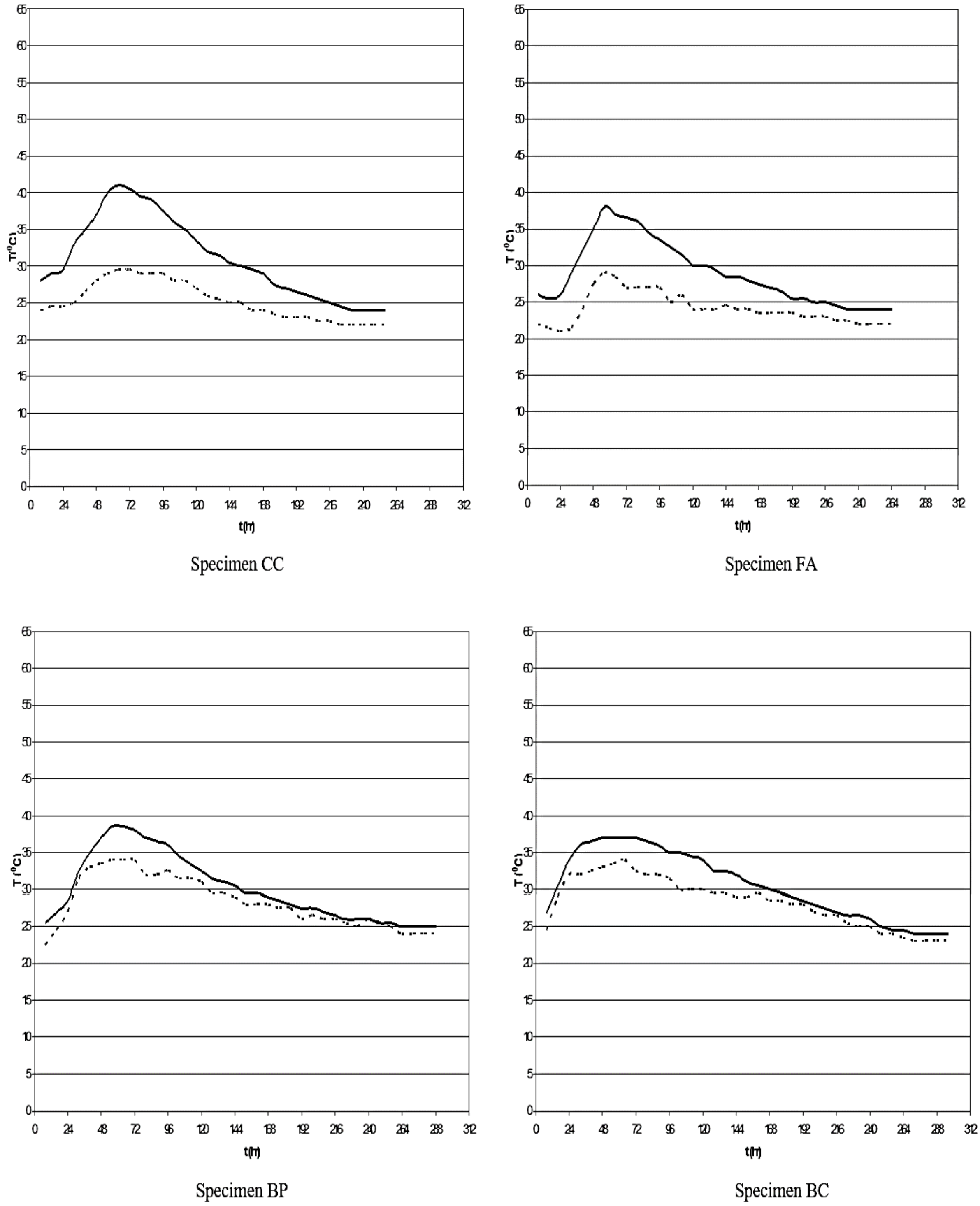
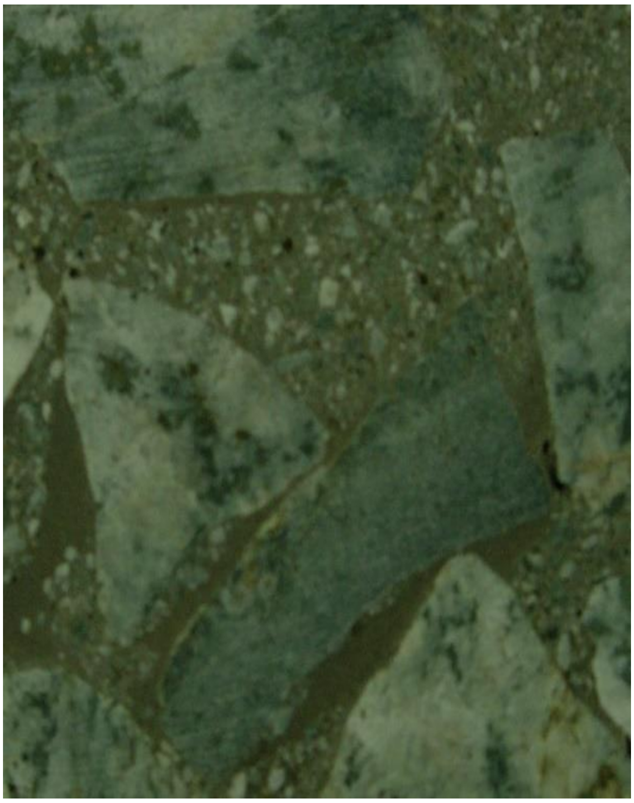
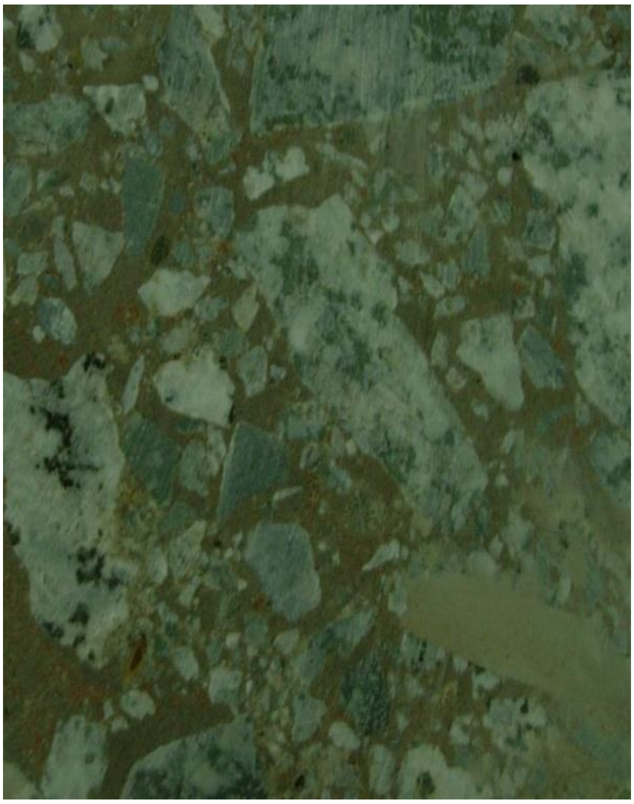



Fig. 4. Concrete Temperature ( ———— middle, - - - - - surface)

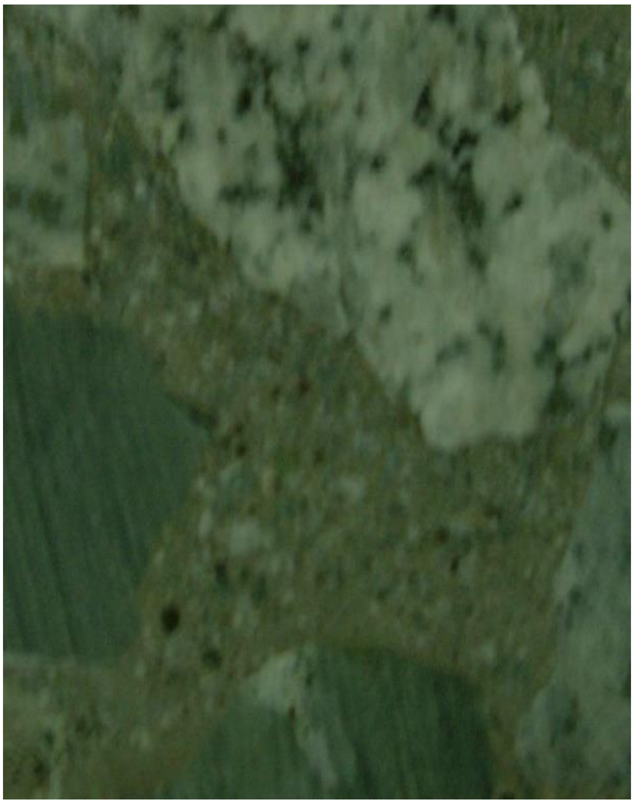
Specimen CC



Specimen FA



Specimen BP



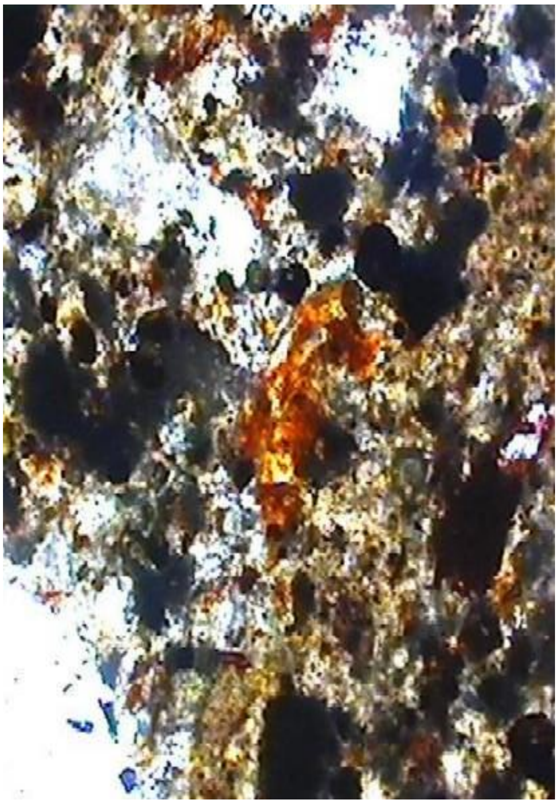
Specimen BC

Fig. 5. The Appearance of the Specimens at Macro Scale (1 to 1)

Specimen CC

Specimen FA

Specimen BP



Specimen BC

Fig. 6. The Appearance of the Specimens at Micro Scale (1 to 25)

### 3.2. Mechanical Properties

Table 6 shows concrete core compressive strength and elastic modulus data at ages 28, 90, 180, 360, 540 and 720 days. The concrete specimens produced by PAC-SCG method gave strength values equal or greater than those of the reference specimen CC at all ages. The concrete specimens FA and BC gave strength values that were close to each other at all ages, which is not surprising because the total percentage of pozzolanic addition was same and the mineral admixture was fly ash in both the specimens. The surprising result was with brick-powder concrete (BP) because at early ages this concrete gave strength values close to FA and BC; however, at later ages (180 days and more) much higher strength values were obtained.

In regard to the elasticity moduli, according to the published literature the modulus of elasticity of PAC is usually more than half of that of conventional concrete (Waterways Experiment Station, 1954; Davis, 1958; Davis, 1960).

Table 6. Mechanical Properties

| | | Specimen | | | |
|---|---|---|---|---|---|
| | | CC (Mpa) | FA (Mpa) | BP (Mpa) | BC (Mpa) |
| 28 days | σ | 15.6 | 16.5 | 15.9 | 14.6 |
| | E | 22565 | 16033 | 15879 | 11408 |
| 90 days | σ | 18.7 | 19.9 | 19.9 | 18.9 |
| | E | 26837 | 25930 | 19874 | 17825 |
| 180 days | σ | 20.6 | 21.9 | 24 | 21.3 |
| | E | 28571 | 26662 | 25816 | 20499 |
| 360 days | σ | 22.9 | 23.4 | 27.8 | 23.1 |
| | E | 29335 | 29944 | 30909 | 22678 |
| 540 days | σ | 23.7 | 24.4 | 30.8 | 24.2 |
| | E | 30287 | 31602 | 34375 | 24204 |
| 720 days | σ | 24.5 | 25.1 | 32.9 | 24.8 |
| | E | 31952 | 32591 | 36446 | 25223 |

σ: Compressive Strength (MPa) ; E: Modulus of Elasticity (MPa)

In this study, this was the case for the elastic moduli up to 180 days, however, the values were either similar or slightly higher for FA and BP at later ages than 180 days. The formulae used for conventional concrete to predict the modulus of elasticity from the compressive strength do not provide reasonable results for conventional PAC specimens (Abdelgader and Górski, 2002; Abdelgader and Górski, 2003). However, for the PAC-SCG specimens, when the expected modulus of elasticity values calculated from the corresponding compressive strength values by the formula offered by ACI (ACI Committee 318, 2015) taken into account, it is seen that after 90 days, the observed values are either more or less similar to predicted values, or even higher.

## 4. CONCLUSIONS

A new method of making preplaced aggregate concrete has been investigated for mass concrete construction. For this purpose, four cubes of concrete, each with a volume of 1 m and with different mix designs, were prepared, and the specimens have been examined from thermal and mechanical properties points of view. As a result of the experiments carried out, the following conclusions have been achieved:

1. The maximum peak temperature difference of 11.5 C was obtained with reference concrete specimen CC. This value does not indicate any risk of thermal cracking; because it is generally experienced that slowly cooled massive concrete structures can withstand a 20 C drop in temperature without cracking (Mehta and Monteiro, 2005**)**. All other PAC concrete specimens made with SCG method showed even a lower peak temperature difference. Thus it can be concluded that the PAC-SCG method is very effective in mitigating the risk of thermal cracking in mass concrete.

2. The PAC method using the new technology of self-compacting mortar for grouting the pre-placed aggregate (PAC-SCG), is even more effective in mitigating the risk of thermal cracking by lowering the maximum peak temperature as a result of reduced initial temperature of freshly placed concrete.

3. The PAC-SCG method produced concrete specimens with compressive strength and modulus of elasticity values comparable to that of conventional concrete at early ages, and somewhat higher values at later ages. Although the tensile strength of the PAC specimens were not determined experimentally, by applying the formula suggested by Abdelgader *et al.*, 2006 it can be concluded that PAC is also more advantageous from tensile strength point of view than conventional concrete. This is important in mass concrete to avoid the tensile cracks caused by temperature changes.

4. It is already known from the feasibility study of the restoration of Barker Dam that the cost of mass construction by PAC method is less than that of by conventional concrete (Baumann, 1948). It is obvious that the cost of mass construction can be reduced further by the new approach offered in this paper, since the needs for special equipment and skilled labor are eliminated.

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