# Cooling Concrete Aggregates: Challenges in Design and Simulation

K. I. E. AHMED [(1)], A.M.S. HAMOUDA [(2)] AND M. S. GADALA [(1)],

(1) Dept. of Mech. Engineering
The Univ. of British Columbia
Vancouver, BC, CANADA

(2) Dept. of Mech. Engineering
Qatar University
Doha, QATAR

***Abstract:*** Using hot aggregates in concrete making results in drop in compressive strength of the produced concrete. Various methods have been proposed for cooling concrete aggregates. In this paper we propose a modified design for a cooling drum to be used in this regard. Preliminary simulation of the heat flow during the cooling process in the drum is analyzed with the objective of optimizing the design and achieving minimum cooling time with the least possible power. A finite element model for the new design is proposed and discussed. Many of the challenges facing the numerical simulation are addressed. The results of the finite element analysis of the modified design are presented and compared with similar ones in the literature.

***Key-Words:*** Cooling porous material, convection heat transfer, finite element, cooling drums.

## 1. Introduction & Review:

Ready-mixed concrete manufacturers, in hot weather regions like the Gulf area, are faced with drops in compressive strengths of concrete produced in summer. High ambient temperatures increases the rate of evaporation from fresh concrete resulting in lower effective water content and hence lower effective water-cement ratio per weight [1-2]. As shown in figure (1), a reduction of compressive strength has also been observed on specimens produced under controlled environment and tested in laboratory [3]. High temperature speeds cement hydration and the bonding between the cement grains becomes weaker. Therefore, the early-age strength increases with higher curing temperatures because the reaction rate is faster, but 28-day strength decreases because of the poor bonding between cement grains. It is noted that higher temperature aggregates results in greater concentration of calcium hydroxide at the interface. This observation leads us to assume that the transition zone might be weakened by chemical phenomenon due to the rise of the constituent temperatures [3].

The two main classes of hot climate are `hot-wet' and `hot-dry'. The common denominator is that heat accelerates chemical processes and it is vital to protect newly placed concrete against high temperatures. In hot-dry conditions, evaporative forces are high and, therefore, special care must be taken to prevent drying out and to retain the required water content in the concrete for hydration. While this may be less of a problem in hot-wet conditions with high humidity, the opposite danger exists, as rain may lead to an excessively wet mix, and may disturb the water balance for hydration and strength gain [4].

The Gulf weather conditions are mostly associated with hot weather most of the year. The weather may fluctuate between summer temperatures reaching nearly 50ºC and winter temperatures with a minimum of 18ºC. Relative humidity follows a similar pattern ranging between 5% and 90% from inland to coastal regions, respectively, see figure (2). Ready-mixed concrete manufacturers have to accommodate these extreme highs and lows in climate statistics [5].

Aggregate temperature plays a very important role in defining the concrete mix temperature [6]. It was believed that the aggregate temperature has to be less than $2^oC$ to have a concrete mix temperature less than 10 $^oC$. However, it was shown that keeping the aggregate temperature about 15 $^oC$ is adequate in achieving proper results [6-7].

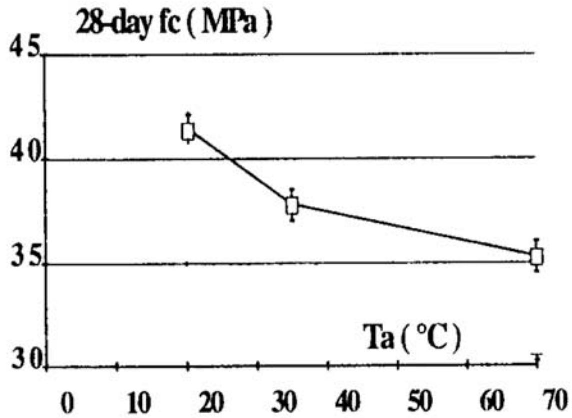


Figure 1: Effect of aggregate temperature on the 28-day concrete compressive strength [3].

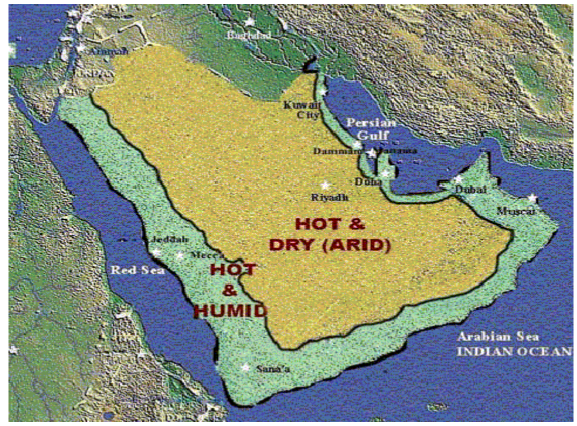


Figure 2: Different climate regions within the Arab peninsula [5].

Concrete mix temperature may be reduced through several methods. Cooling the mix ingredients, using chilled water, crushed ice, or liquid nitrogen are some of the available options [7].

Cooling the concrete aggregate is one of the most effective methods to reduce the concrete mix temperature. Different equipments are developed for that purpose. Among these are belt conveyors, cooling drums, chilled storage rooms, and a mix of various methods [8-10]. In these equipments, cooled air, liquid nitrogen, chilled water, or ice are used to reduce the concrete mix temperature. Ice and chilled water are usually added to the mix to keep water balance of the concrete mix under control. Liquid nitrogen is mostly used to reduce the cement temperature to avoid concrete aggregate thermal shocks. Cooled air is the preferred candidate, although this requires huge flow rates and extensive cooling systems.

Although the above problem is crucial for concrete makers, there is very little work in the literature to address the numerical or the experimental simulation of the problem and to optimize the cooling facility. Most of the available work presents industrial experiences and developments [8-10] and food cooling systems.

Cooling using air jets over belt conveyors is, probably, the cheapest and easiest method. However, concrete industry reports long cooling time, low cooling efficiency, large occupied space and low production rate. On the other hand, cooling drums are very compact, efficient, and provide high production rate. Cooling drums entail, however, the disadvantages of being quite expensive, consume high mechanical power, and are relatively difficult to maintain.

The heat flow during the cooling process, either by belt conveyors or drums, needs to be analyzed and optimized to achieve short cooling time with low cooling power. The main objective of the current work is to propose a design modifying for cooling drums and to present a numerical simulation for the cooling process using the finite element method.

## 2. Proposed Design and Challenges:

The current work is focused on cooling aggregates of limestone, gabbro, and sand. Typical values of the thermo physical properties of these aggregates are shown in Table-1 [11-12]. It is worth noting that the thermal conductivities of the concrete aggregates are very low. Furthermore, due to the porosity nature of the concrete aggregates (10%-50%) the thermal conductivity would deteriorate at a very high rate; e.g., the thermal conductivity of limestone decreases by about 70% for a porosity of 10% [11-12]. This low thermal conductivity highly resists the stored heat in the aggregates from moving towards the colder surfaces. The cooling process in the existing drums in the market is based on mixing the aggregates to enlarge the contact area between the aggregates and the cooling air. The convection to the cooling air is the main heat transfer theme in these previous designs and cooling through the thermal contact between the aggregates and the cold drum body as well as the mixing process was not optimized.

Table 1: Thermo physical properties of the aggregates

| | Density (kg/m$^3$) | Thermal Conductivity (W/m$^2$.°C) | Specific heat (J/kg.°C) |
|---|---|---|---|
| **Air** | 1.2 | 0.025 | 1012 |
| **Limestone** | 2320 | 2.1 | 810 |
| **Gabbro** | 2800 | 2.0 | 1000 |
| **Sand** | 2020 | 1.9 | 835 |

Figure (3) shows a schematic drawing of a cross section in the proposed design of the cooling drum. Spiral donuts (rings) and axial webs are welded inside the drum in such a way to facilitate slow axial movement of the aggregate as the drum rotates. Openings in the external body of the drum ensure enlarging the cold surface areas in-contact with aggregates and also enhance the cooling of the internal spiral donuts.

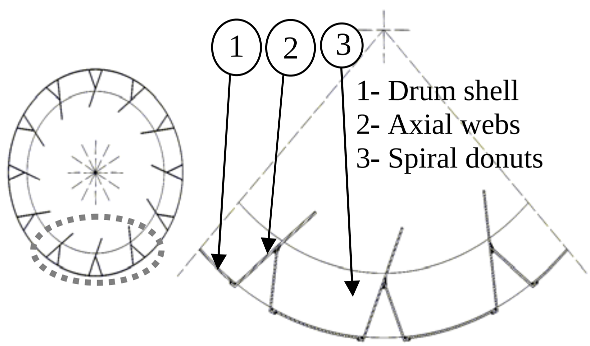


Figure 3: Detailed drawing of a cross section in the cooling drum

Challenges in the numerical simulation of the problem are numerous. The problem is a 3D one due to non-symmetric cross section of the drum and the boundary condition changes along the drum length as shown in Figure (4). The aggregate surface interfacing with cold air is excessively rough, particularly with coarse aggregates. Due to the voids between the aggregates particles, convection would play an important role in the heat transfer problem and it is quite difficult to make accurate assumptions or experimental measurements for the heat transfer coefficient. Also, it is difficult to assess the thermal contact resistance between the aggregate and the drum surface (Figure-5).

Simulating the continuous mixing of the aggregate and the aggregate radial falling and axial travel through varying temperature zones would present another challenge (Figure-5). Although the free falling of the aggregate is for a short distance (approximately 1.5-2.0 m), the heat transfer during this action would be important because of its repetitive nature. The first layer of aggregate interfacing with the cold air and that in contact with the drum body would be thermally behaving as an aggregate with zero porosity. However, the porosity will significantly reduce the thermal conductivity of the inside layers of the aggregate core.

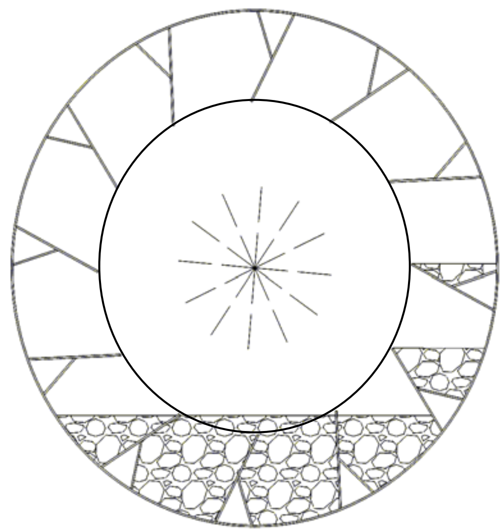

Figure 4: Cross sectional view in the cooling drum

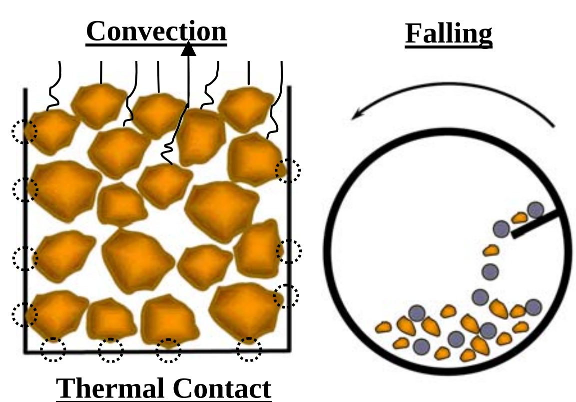


Figure 5: Convection, contact and falling problems

## 3. The Finite Element Model:

A finite element model is developed using the commercial code ANSYS to compare the cooling behavior of the proposed changes in the design, Figure (6). The drum is made of steel sheets and has 12 pockets with depth of 1 m and opening angle of 45$^o$ starts at the end of the spiral donuts which has width of 0.6 m. The empty drum has a repeated pattern which is the shaded sector in Figure (6). The drum is assumed to have four pockets filled with 0.6 m aggregate height all the time. The rest of pockets are assumed empty. After one third of a drum revolution the four pockets are assumed to fully pour the aggregate into the neighboring four pockets. Two drum revolutions are studied at 1 rpm, and 3 rpm speeds.

Three pockets are modeled, one filled with sand and the other two pockets are empty. This 2-D approximation may not be suitable for obtaining specific results; however it is acceptable for our present comparative study. The finite element model is shown in Figure (7). The contact between sand and pocket body is defined with thermal contact elements represented by a white line in the Figure. The thermal contact resistance between the steel body and sand are defined according to [13]. The internal and external surfaces, of the filled and empty pockets, are assumed to have forced cooling air at -15$^o$C with heat transfer coefficient of 20 W/m$^2$.K and 40 W/m$^2$.K, respectively. The initial temperature of the aggregate is assumed to be 50$^o$C.

Temperatures from the heat transfer analysis are obtained for one third of the drum revolutions. Then, temperatures of the upper pocket are transferred to the middle pocket, those of the middle are transferred to the lower and those of the lower are transferred to the upper. Also temperatures of the aggregate content are re-applied to random locations within the aggregate to simulate the mixing process. These re-applied temperatures for the aggregate and the pockets body are considered as initial conditions to the next one third of the drum revolution. For each drum revolution this mechanism is repeated three times.

The spiral donuts of the drum are assumed to be 1m pitch. This means that for each drum revolution, the sand moves forward one meter. Along the length of the drum, a total of nineteen compartments are modeled similar to the above model. After one full revolution, the resulted temperatures of the aggregate of each compartment are moved forward to the next compartment with random allocations and the temperature of the aggregate in the first compartment is re-initialized again to 50$^o$C simulating new fed to the drum. Finally the resulted temperatures of the aggregate of the last compartment are averaged to report the final output temperature.

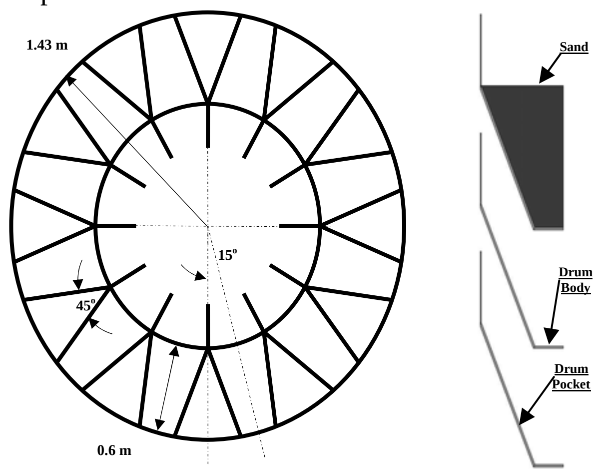


Figure 6: Cross sectional view in the cooling drum with the 2-D approximation

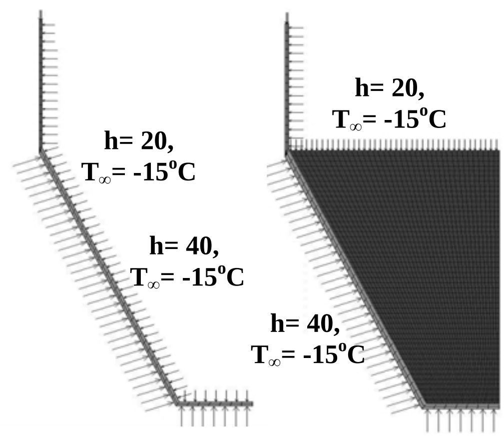


Figure 7: FE model and boundary conditions of the empty and filled pockets

## 4. Preliminary Results and Discussion

Figure (8) shows the sand temperatures at the exit of the cooling drum. The first patch leaves the drum after 10 minutes, for 1 rpm drum speed. There is no difference between the old and new designs at the beginning because the drum body temperature is initially at -15$^o$C. However, by the time the drum body gains heat reaching steady state, the difference in results is significant and reaches 5$^o$C. This difference increases along the length of the drum. The temperature distributions of the sand within the drum pockets for the new and old design are shown in Figure (9, 10).

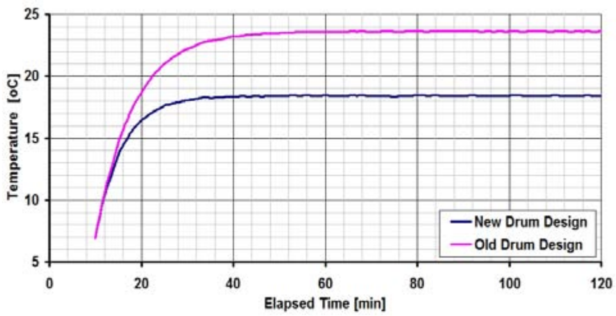


**Figure 8: Average temperature of the sand at the drum exit.**

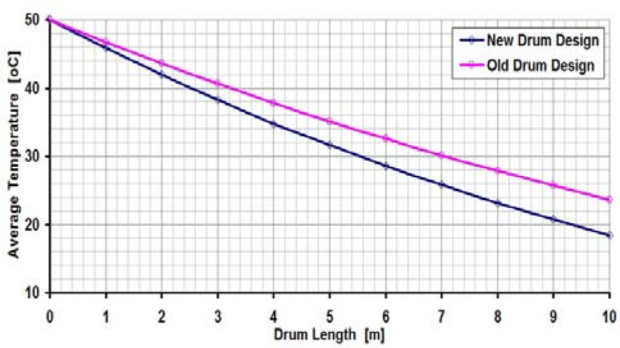


**Figure 9: Sand temperatures through drum pockets.**

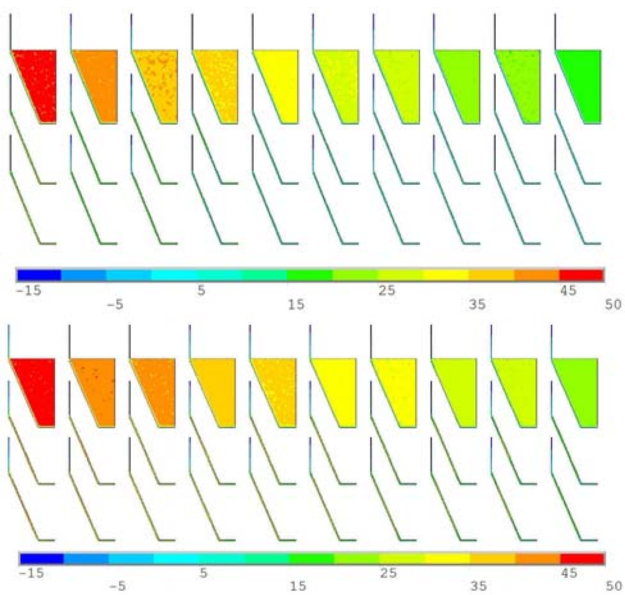


**Figure 10: Sand temperature distribution through drum pockets.**

Aggregate falling is simulated by super-position. A separate model of a ball of aggregate with 20 mm diameter falling in cold air of -15 $^o$C is studied under the effect of heat convection around the ball surface. The result of the model is then approximated and fitted to an empirical equation that calculates the new temperature of the aggregate according to its initial temperature just before falling. The simulation of aggregate mixing and falling are interpreted into a special user subroutine using the APDL language offered by ANSYS. The empirical equation of the sand falling is used in the solution subroutine to calculate the temperature of the sand after each falling and to apply this temparature as an initial condition for the next solution step. The results and the empirical equation are shown in Figure (11).

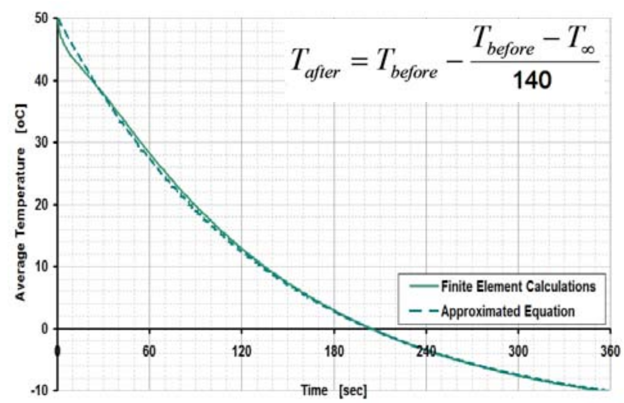


**Figure 11: The Sand falling simulation model results and the empirical equation.**

## 5. Conclusions

Cooling concrete aggregates is a crucial factor in hot weather region like the Gulf area to retain the concrete strength. Existing cooling methods and drums in the literature are not optimized for power and cooling time minimization. Most of the existing designs perform some mixing of the aggregates in a cold environment. These designs don't utilize the full advantages of proper mixing, free falling of aggregates and extended metal surface area for heat convection. A new design is proposed and analyzed using finite element simulation tools to account and to make use of the above factors. Challenges in the design and the numerical simulation of the cooling process in the new design have been identified and discussed. The simulation results showed the importance of enhancing the cooling conditions of the drum body to get lower aggregate output temperature with reduced power.

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