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An innovative approach for temperature control of massive concrete structures at early ages based on post-cooling: Proof of concept

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ABSTRACT

This study proposes a new methodology for the embedment of flexible PVC hoses (with the shape/geometry of the intended cooling pipes) that allows their removal a few hours after casting (i.e. after setting), while allowing that water is pumped through the circular cavity afterward (through a flexible/impermeable sleeve placed to shield the exposed concrete cavity). The PVC hoses are initially filled with oil under pressure, which are deflated a few hours after casting (particularly after setting is identified), and removed without relevant constraints due to their reduction in diameter inherent to deflation. All components and materials embedded into concrete (hose, sleeve) are fully recoverable after the end of the temperature control period, avoiding the loss of materials, with important financial and sustainability gains. This paper intends to show the proof-of-concept carried out in laboratory context conditions, highlighting the features that led to the selection and phasing procedure of the solution proposed.

1. Introduction

Hydraulic concrete structures, bridge structures, and foundations of large buildings are normally built with thick cross-sectional sizes. The heat released by cement hydration in such massive blocks under natural conditions is very slowly conducted towards the surrounding environment and the differences in temperature between the core and surface areas of the massive concrete structures can reach significant values [1,2], particularly for the instants of peak temperatures in the core. The thermal cracks that might result from the stresses caused by restrained thermal deformations (either due to cross-sectional restraint or external restraint) can cause important problems to performance indicators such as durability and tightness [3]. Furthermore, it is known that the peak temperature in massive concrete structures should be limited, as to avoid potential delayed ettringite formation (DEF) which causes long term cracking that compromises structural integrity [4].

As to minimize risks of thermal cracking, one of the techniques to adopt (amongst others) is the control of temperature differentials under a threshold level and limiting maximum temperature [5]. These are, however complex to handle due to the set of parameters that influence temperature development in concrete, such as: environmental temperature (both during casting and following curing period), relative humidity, wind velocity, solar radiation, initial temperature of the concrete, heat generation potential of the binder in the mix, curing methodology, size of the massive concrete element, geometrical connection to adjacent elements, etc.

Many solutions have been proposed to reduce the maximum temperature in the massive concrete such as [6]: (i) pre-cooling methods (including cooling of constituents, cooling during production phase); (ii) post-cooling of concrete (including embedded pipes by circulating cooling fluid); and (iii) construction phasing (considering the trade-off between the desirable height of casting lifts combined with small waiting periods for casting).

Amongst all methods mentioned above, post-cooling of concrete method is one of the most popular and effective methods, particularly through the application of active circulation of cool water within a pre-embedded cooling pipe system [7–11].

Controlling cooling pipe system parameters is an important approach

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to control the temperature during construction activities. This technique was introduced in an extensive manner for the first time in the construction of the Hoover Dam in 1933 in the United States, by embedding a significant length of pipes (about 1352 km length) within the structure [12]. Since then, the use of cooling pipe systems to control temperature in massive concrete has been applied in many countries for more than 70 years [13].

The working principles of cooling pipe systems for concrete are relatively simple. A good knowledge of such principles and the properties of the materials involved allows to design the system in terms of: the temperature of the cooling fluid (normally water); the velocity of fluid circulation; the time of activation and duration of fluid circulation; the geometry and type of pipes (their diameter, material, layout) [14].

Although, post-cooling pipe in the concrete system can lead to reduction of temperature variations that would otherwise be attained, this technique raises some important issues in regard to the cost and non-reusability for pipe material itself, despite the fact that it is normally only necessary at early ages (first weeks). This can be perceived as a drawback, when the sustainability of the use of materials is concerned.

This paper proposes a new methodology for post-cooling of massive concrete that overcomes the non-reusability of the pipe material, by establishing means to reuse the entire set of materials and components of the cooling pipe system, while keeping operations practical (easy operation).

To ease the problem of re-usability of the pipes in massive concrete structures, a simple setup, based in the embedment of a PVC hose under pressure (oil), has been attempted to enable the hose to be deflated a few hours after casting (i.e. practically immediately after setting). Upon removal of the PVC hose (pulled from one extremity), a flexible thin sleeve is inserted into the cavity generated by the hose (being attached on the opposite extremity of the PVC hose and pulled in, as the PVC hose is being pulled out). After the flexible thin sleeve is in place, water can be circulated through its interior without any risk of damaging the surrounding concrete, as only thermal changes are allowed (e.g. impossible for water to permeate into concrete, or aggregates/paste to be washed out by water circulation).

In practice, a hose is placed with the intended layout at the base of a given casting lift, with the shape intended for the cooling pipe layout, and oil is pumped into the hose, thus increasing its diameter, without changing its layout. Then, pouring of the concrete can be done and at the end of setting time of the concrete, the oil is removed from the inside of the hose, and its diameter is reduced (and easily demoulded/detached from the surrounding concrete, which is self-sustainable at this stage). Then, the hose can be pulled out from concrete with ease, and be re-used for the following casts (as well as the extracted oil). The circular cavity created by the removal of the hose is then used for circulation of the cooling fluid (e.g. water), through the flexible/impermeable sleeves mentioned above. These sleeves that can be easily pulled in upon removal of the hoses to initiate water circulation during the intended duration. The sleeves can be recovered at the end and the circular cavities can then be closed or integrally filled with cement paste or rich mortar.

The aim of this study was to carry out laboratory scale tests to support the proof-of-concept of the proposed method, demonstrating its application based on a set of pilot experiments.

2. Post-cooling of massive concrete with water circulation

The purpose of post-cooling with embedded pipes is to control internal temperature of concrete within specific limits by circulating water through the piping system in order to mitigate the risk of thermal cracking of massive concrete.

The technique is quite effective and mostly suitable for massive concrete structures (for internal cooling [15]) due to the relatively low costs of effective design, material procurement, installation and operation [16]. These systems can be activated during early ages up to several weeks after casting as to control temperature of the massive concrete.

Many applications in the literature typically report the use of 1" (2.54 cm) diameter steel pipes with wall thickness of 1.5 mm [16]. Alternatively, aluminium pipes (only less than 3 months duration), PVC, polyethylene or other plastic-based pipes are recommendable for cooling applications with special care in respect to the mechanical strength of the piping system [17]. The main benefits of using plastic pipes, when compared to steel pipes, are the lower cost, the lower thermal conductivity (minimizing the heat absorption of the flowing fluid along the embedded path of the pipe, thus allowing application of longer piping systems). Furthermore, the plastic based pipes are flexible thus allowing easier and fast placement/installation than that of steel pipes. However, the cooling capacity is lower than that of steel pipes.

In several types of massive concrete structures, particularly dams and blocks, cooling pipes are usually placed at the top of the last casted concrete block, which corresponds to the bottom level of the block of subsequent casting phase.

An example of the post-cooling principle and pipe layout configuration in the scope of the construction phasing of a dam structure and the expectable impact of post-cooling strategy on the temperature drop of massive concrete are illustrated in Fig. 1.

The distribution, material type and number of pipes, horizontal/vertical spacing between the pipes can influence the efficiency of the system which needs to be in the line with thermal design. According to CIRIA C660 [18], horizontal spacings between pipes can be 1.0 m for large casting of low-heat cement whereas 0.5 m spacing is recommended for concretes that generate higher heat. It is frequent to observe quincunx arrangement of cooling pipes for optimization of horizontal and vertical space between pipes [16]. According to the recommendations of ACI [19] the length of the pipe, can be as long as 180–350 m without relevant heating of the cooling water (hence, loss of efficiency of cooling throughout the pipe's length). Regarding the flow rate of the water the value 15–17 L/min is recommended [5] which corresponds to ~0.6 m/s water velocity, in case a 1″ inner diameter of pipe is considered. Natural sources of water (e.g. from a river or water basin) with natural temperature are normally considered adequate for the purposes of concrete cooling (with acceptable temperature difference between circulating water and surrounding concrete below 20 °C) [20].

The operation of cooling pipe systems demands for a water-tightness test to be made before casting [16]. Also the pressure inside the pipes needs to be monitored as to ensure the desirable flow rate during operation. Activation of water circulation can be made simultaneously with the casting operations, but this is not normally done, as to avoid damage to the fresh concrete due to vibration of the pipes inherent to the water circulation. Indeed, as the heat generation of concrete is quite low before the setting time, it is feasible to await for such threshold in order to activate the circulation of water, which occurs well before the peak temperature of concrete is reached, and prolonging the circulation up to a scenario or condition in which the thermal equilibrium between core of concrete and outer environment is nearly attained [21] (or at least up to well after the peak temperature has been reached in the concrete core).

The system to be proposed herein has been tailored to fulfil the following main set of performance requirements: (i) reusability of all parts and materials involved; (ii) capacity to activate cooling pipes at periods compatible with demands on control temperature; (iii) water circulation does not causing damage of leaching to concrete; (iv) simple and practical without demanding special or costly equipment or force induction. The following section presents and discusses a set of pilot experiments that were aimed to test the proposed method/idea and demonstrate its capacity to satisfy the minimal performance requirements listed above.

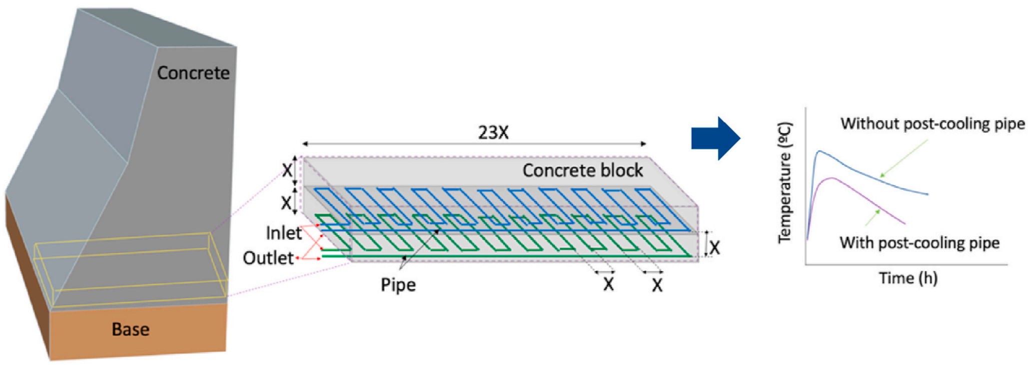

Fig. 1. 3D model example of a massive concrete structure – dam – with enlarged representation of two concrete blocks including practical layout of post-cooling pipe scheme with inlet/outlet positions for water circulation and the graph presents temperature of concrete with and without activation of post-cooling pipe over time.

3. Proof of concept: pilot experiments

3.1. Materials and methods

3.1.1. Selection of materials for the pipe

The selection of the material and pipe diameter for creating the continuous circular cavity inside the concrete was chosen based on existing knowledge of common pipe materials (as discussed in the previous section) used for post-cooling of massive concrete structures. Moreover, the following parameters were also taken into account: flexibility for following a given path; internal working/rupture pressure compatible with the use of a manual pump at relative low pressure values (e.g. below 10 bar); stiffness of the pipe, so that the input of a given internal pressure can produce a significant variation in diameter; smoothness of exterior pipe surface (to avoid significant chemical adhesion to the surrounding concrete); and pipe cost, looking particularly into pre-existent solutions in the market for other purposes (e.g. garden hoses or suchlike), in order to maximize cost-effectiveness. Therefore, the initial selection of pipe material was limited to those that allowed satisfying the mentioned constraints.

Based on the reasoning made so far, the hose "Jardibest Country 3" from Heliflex Co. [22] composed by three layers of standard PVC compositions was selected as it is readily available in the market, with an interior diameter of 19 mm, wall thickness of 3.5 mm, weight of 0.3 kg/m, working pressure of 10 bar and ultimate pressure of 25 bar. The hose (hereafter named as "pipe") is extremely flexible as it is reinforced with polyester yarns, has a smooth outside surface, resistant to oil, greases and fuels, and is available in length over 100 m, according to the

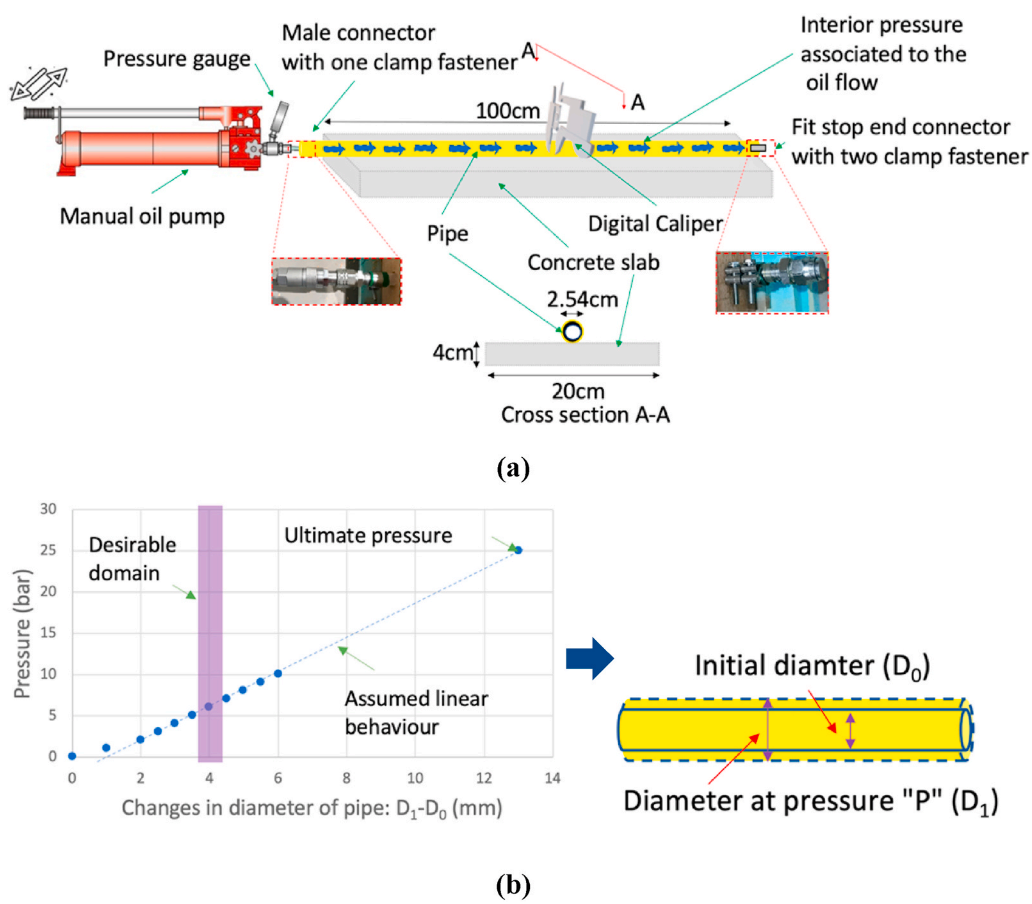

Fig. 2. (a) Test setup scheme and the influence on diameter change of the pipe; (b) Relationship between pressure and diameter change of the pipe. Units: cm.

information provided by the supplier [22].

A first experiment was made in order to assess the changes that oil pressure can induce in the diameter of the pipe when laid on a surface (i.e. free to expand), as to select the oil pressure level to introduce for the pilot experiment embedded into concrete. In accordance to the scheme shown in Fig. 2a, the selected pipe for this research was subjected to an oil pressure injection by using a manual oil pump from ENERPAC, Hydraulic Series, equipped with manometer model TRALE with a precision of 1 bar. A fit stop end connector (male) with two clamps fastener (circular shape) was considered for one extremity of the pipe and one male connector with one clamp fastener was used for another extremity that it connected to the pump's nozzle. All the connectors and clamps utilized in this research were made of stainless steel. Diameter of all used clamp fasteners was of 20–32 mm.

The diameter of the pipe was measured and marked using a digital calliper with precision of 0.01 mm. The observed relationship between the imposed pressure by the manual oil pump and diameter change of the pipe is shown in Fig. 2b. The relationship between imposed pressure and changes in diameter was obtained when the oil is pressurized (here named as "P"). In the following descriptions, the initial diameter of the pipe designated as "D_0" and the final diameter after imposing a given pressure designated as "D_1". Such values ascribe the ability of the pipe to expand its diameter while undergoing a given pressure. As shown in Fig. 2b, the application of 8 bar pressure increases the diameter of the pipe by 4.5 mm ($D_1 - D_0$). This was considered desirable for the type of application, taking into account empirical observations (before casting) on the diametral expansion/contraction of the deflated pipe as compared to the inflated pipe, when relevant bottlenecks were considered (e.g. fixation nails, holes in the formwork).

Indeed this means that the pipe with 26 mm initial diameter was expanded to 30.5 mm: therefore, upon being embedded into fresh concrete with 30.5 mm, this pipe is expected to actively be reduced to 26 mm diameter upon deflation, expectably exerting enough detaching force that allows it to completely be separated from the surrounding hardened concrete (e.g. right after setting). The internal pressure of 8 bar is very far from the ultimate pressure capacity of the pipe as defined by the supplier (25 bar). Assuming a linear relationship between the changes in diameter of the pipe and the pressure, imposing around 22 bar pressure, would safely increase the diameter of the pipe by ~50%, if required.

An additional remark is given in regard to the reasoning for choosing oil as the medium to impose pressure to the PVC hose, rather than water or other fluid. Oil hydraulics are known to be readily available at cost-effective solutions in the market for the purpose of keeping pressure constant. When compared to the use of water, oil has other advantages in view of features such as lower corrosion proneness, better lubrication and even lack of potential for organic and fungi growth. The potential disadvantage of environmental contamination is mitigated by the fact that the oil is fully recovered at the end of the cycle, and it only comes into contact with the inner lining of the PVC pipe (never with casted concrete, for example).

3.1.2. Inner lining of hollow concrete

The selection of material/solution for the circulation of water within the circular cavity created upon removal of the pipe was based on the following required/desirable features: to be used in direct contact with concrete without undesirable behaviour (e.g. chemical interaction with hardening concrete), flexible in both longitudinal and cross-sectional/transversal direction (as to adjust well to the cavity created by the removal of the pipe), cost-effective (preferably based on something commercially available). Based on this premise, a heat shrink tube with reference "CYG CB-HFT TUBE 25.4" and based on polyolefin [24] as a flexible/impermeable sleeve was selected as it is readily available on the market, and it does have any expectable interaction with fresh concrete constituents. This tube has an inside diameter 25.4 mm, wall thickness of 0.5 mm, shrink temperature of 90 °C, tensile strength 10.4 MPa (averaging 7.3 MPa), radial shrinking ratio of 50%, ultimate elongation of 200%, available in length over 30 m and is water proof, according to the technical sheet provided by supplier [23].

3.1.3. Mix design and characterization of the concrete

The construction of small scale test prototypes involved the necessity to cast concrete, and needed to be somewhat representative of the procedure of concrete casting of a massive structure. The selected mix contained: Portland cement type II class 32.5R from CIMPOR company, Portugal; river sand (0/4 mm) and fine sand; gravel (8/12 mm); gravel (12/25 mm). The particle size distribution of the aggregates is presented in Fig. 3. The preconditioning of all materials was done according to the recommendations of the RRT^{+} program of COST action TU1404 [24].

Only one formulation of concrete is studied herein and is presented in Table 1.

The aggregates were kept inside the oven to be dried for three days and then kept one day at laboratory environmental conditions before casting. The following mixing procedure was used: sand (0/4 mm) is introduced in the mixer, being mixed for 30 s, then filler (fine sand) is added and everything is mixed for 60 s. Then, cement is added and everything is mixed for 60 s. Then, gravels (8/12 mm and 12/25 mm) are introduced and everything is mixed for 60 s. During the 30 s, water is progressively added without stopping the mixer and everything is mixed during an additional 60 s.

Then, the mix was transported by a typical wheelbarrow and poured into the formwork. A standard vibrator (from TECHNOFLEX model RABIT) with diameter of the vibrating needles of 25 mm and vibration speed of 18000RPM was used as to remove air bubbles and holes from the concrete and obtain a smooth finish, based on the recommendations of EN-12390-1 standard [25]. Once casted, the formwork was covered with a plastic wrapping to avoid water evaporation under laboratory condition.

Regarding compressive strength test of concrete, 3 cubic specimens of 150 mm were kept in the formwork with sealed at top surface under controlled curing conditions with temperature of 20 °C ± 1 °C and RH = 60% ±5% at the age of 28 days was considered following recommendations of EN-12390-1 standard [25].

Before the actual compressive strength testing occurred in the cubes, measurements of ultrasonic pulse velocity (PunditLab, 54 kHz transducers with 50 mm diameter) were taken for each of specimen according to the EN-12504-4 standard [26], through both pairs of smooth opposite faces. An average value of 4.72 km/s (4.79, 4.63 and 4.74 km/s) for the Ultra-Sound Pulse Velocity was obtained. Such value is considered as a "good concrete" grade, according to the table related to the quality of concrete in ASTM standard C597-16 [27].

Afterward, the compressive strength of specimens was tested (using FORM-TEST compression machine) according to EN-12390-3 standard [28]. Results reported herein are average values, and in the case of the calculated compressive strength the value obtained was 29.13 MPa (30.2, 28.5 and 28.7 MPa). The density measurement followed the recommendations of EN 12390-7 [29]. The average of three specimens for the density measurements was 2360 kg/m^3 (2332, 2378 and 2370 kg/m^3).

3.2. Initial attempts

The initial attempts regarded a simple straight aligned pipe embedded within a rectangular concrete beam with dimensions of 20 cm × 20 cm × 100 cm. An extruded polystyrene (XPS) layer with a thickness of 4 cm has been considered over the ground as basis, to facilitate test setup. Then, steel formworks as lateral walls were used over the XPS for the casting of a regulating mortar screed as shown in Fig. 4 (regulating mortar was laterally surrounded with steel formworks and from the bottom surface it was in contact with XPS, as a boundary conditions). This regulating mortar with a thickness of 4 cm was considered under the test concrete layer, as to simulate a rich mortar

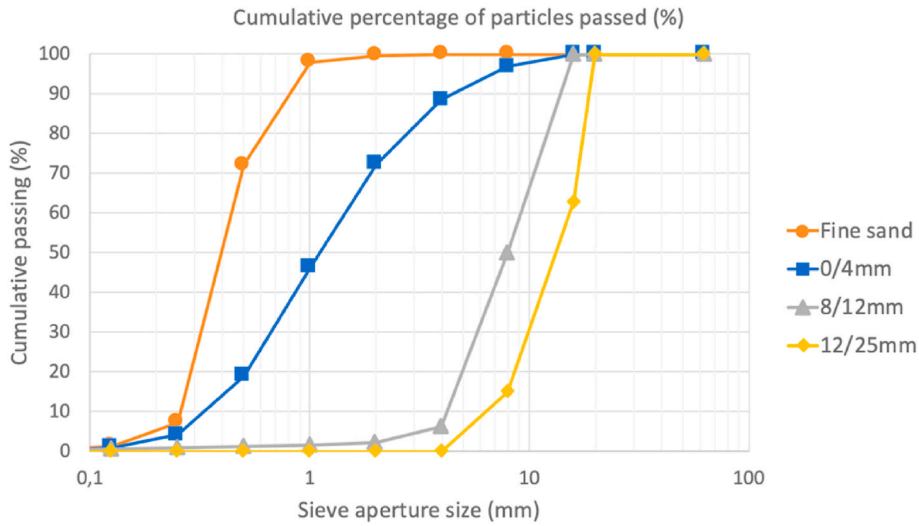

Fig. 3. Particle size distributions of aggregates.

Table 1
Mix design for concretes.

Components (kg/m^3)	Concrete
Cement type II 32.5R	350
Water	175
Sand (0/4 mm)	773.5
Fine sand	136.5
Gravel (8/12 mm)	884.7
Gravel (12/25 mm)	340.2

topping the surface of a previously cast layer (a situation that happens relatively frequently in the sequenced castings on dams, for example). The formulation of the regulating mortar has a composition of: cement 600 kg/m^3, water, 300 kg/m^3 and sand (0/4 mm) 1322 kg/m^3. The experimental set up of the initial attempts is presented in Fig. 4.

In the first attempt, the preparation of the concrete was carried out according to the following phases:

Phase 1- Firstly, the regulating mortar over the XPS with the thickness of 4 cm was casted. After 24hr, the pipe has been placed in the top level of the regulating mortar. Then, the inlet was connected to the manual oil pump by using a male connector and a clamps fastener, as mentioned before. Also a fit stop end connector with two clamps fastener were used for the outlet of the pipe, as to close the system for pumping oil through the pipe. Then, a pressure of 8 bar was imposed to the pipe which was maintained in such condition and ready for casting of concrete (4.5 mm increase in diameter of pipe).

Phase 2- The mixing procedure for the concrete casting has been attempted following the instruction mentioned in section 3.1.3. Once casted, the test concrete prism was covered with a plastic wrap to avoid water evaporation in laboratory environmental conditions.

Phase 3- The 'practical' setting time of the concrete (relevant for assessing the fact that the pipe can be removed from the concrete element without any problems of geometric stability of the recently casted concrete) was determined in a very simplistic 'rule of thumb' method as to correspond to the instant finger penetration into the concrete surface is fully prevented (attained at approximately ~ 6 h after casting), following a quick practitioner test which could be made in any construction site. Then, the pressure of the pipe has been released, with retrieval of the oil to a small reservoir (allowing its re-use). At this time, the pipe diameter deflated to the initial diameter and it was easy to remove the pipe from concrete. For such removal, a longitudinal hand-exerted pull force of about 12 kg (measured with a hand grip dynamometer of 0.1 kg precision) was applied to one extremity of the pipe. It should be mentioned that the required force progressively reduced as the pipe was being pulled.

Phase 4- Immediately after removing the pipe from concrete, cooling pipes were attached to the extremities (inlet and outlet), using silicon material. Note, that this particular initial attempt (reported in this sub-section 3.2) did not encompass any heat shrink tube in between pumped water and concrete, as the possibility of not using any sleeve was still being entertained as potentially feasible (they are however shown herein, as to illustrate pathways that have been confirmed to be unfeasible). Water was circulated at ~0.8 m/s through the circular cavity by using an electrical water pump was connected to the inlet for water circulation by an "open/close valve" from one side and also connected to the "water tank storage" from the other side in order to transfer the water to the concrete system (see Fig. 5). Even though the flow rate of the electrical water pump was not adjustable, it is still in the same magnitude as those recommended by Ref. [5].

The water circulation system was equipped to a fine sieve (No. 63μ), as to monitor any potential washed-out particles (e.g. sand) during the

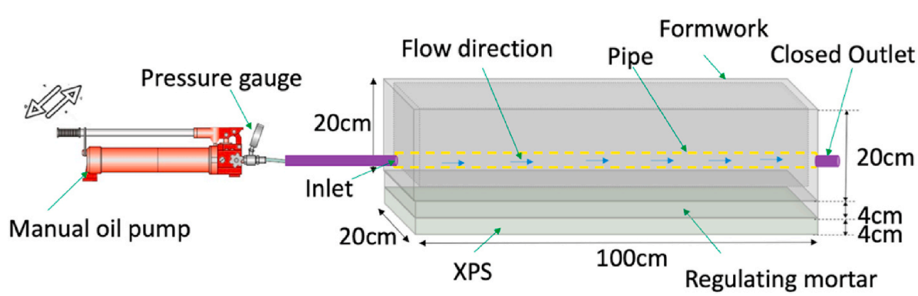

Fig. 4. Scheme of experimental setup of the initial attempts. Units: cm.

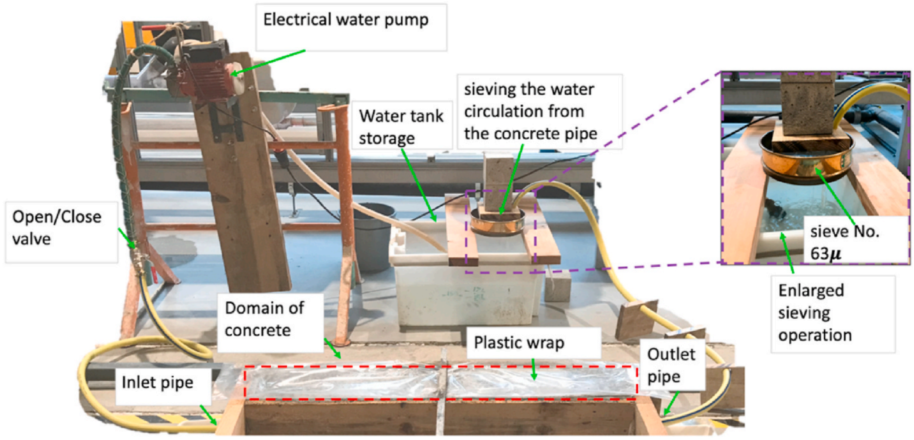

Fig. 5. First experimental setup regarding water circulation.

circulation of water in the system (see enlarged sieving operation in Fig. 5). After 4 days of water circulation, the remained particles over the sieve were dried in an oven with temperature of 70 °C for 24hr, then, they were weighted. Results indicated only a few milligrams of dust and fine particles captured in this sieve, thus indicating that the expectable wash-out of materials of even potential clogging of the cavity have a very low likelihood.

However, it should be mentioned that, during the first attempt, a insignificant water leaked from the extremities (or even sides) was identified, possibly due to the high pressure of the water at the joints. Therefore, an additional measure in order to reduce the water leakage near to the extremities was undertaken in the second attempt.

In the second attempt test, all the phases 1–4 described above have been followed except for the fact that, before casting the concrete, two "O" ring shaped sealings made of silicon with thickness of 5 mm have been attached to the inlet and outlet ends together with a thin layer of 2 mm of silicon material that was also attached to the joints along the regulating mortar, at the internal surface of the wood formwork, as shown dashed lines in cross section in Fig. 6a. Such strategy was considered useful in terms of preventing water leakage from the

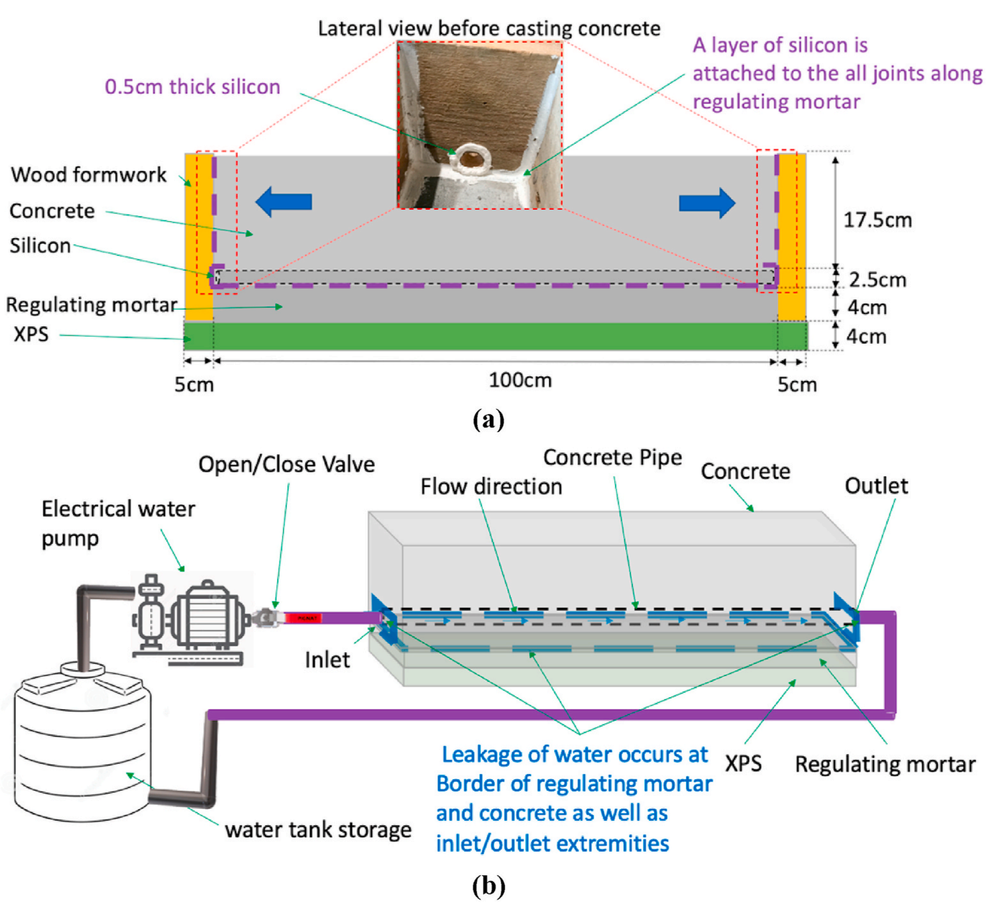

Fig. 6. (a) Cross section of the specimen in the second test setup regarding silicon ring application at the two extremities and a thin layer of silicon at the joints (dashed lines); (b) scheme of observed problem related to the leakage of water from the edges between regulating mortar and concrete plus inlet/outlet extremities. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

extremities and sides. However, after operating about 2hrs of water circulation, leakage of the water was observed through the interfaces of regulating mortar and concrete to the surroundings, as schematically highlighted with "blue dashed lines" in Fig. 6b. This problem is possibly related to the still insufficient connection between the interface of the newly cast concrete and the underlying mortar layer, thus allowing channels of water leakage. In a real case scenario, this would not have been an acceptable situation, not only due to the loss of water, but mainly due to the risks associated to the weakening of the interfaces between the two casting layers. Therefore, despite the fact that more complexity was brought to the system, it was necessary to devise an impermeable interface medium between the generated cavity and the water to be circulated. Such improvement to the system is detailed in the next section.

3.3. Final working prototype

Based on the lessons learned from the previous attempts, a final prototype was prepared, with two fundamental differences: (i) a heat shrink tube was added right after the removal of the pipe, as to operate as an inner lining of the hollow cavity left, while allowing the circulation of water in the concrete; (ii) the geometry of the cooling system was made more complex by introducing a "U" turn in order to demonstrate that it is possible to produce/emulate the typical patterns of post-cooling pipe systems.

In regard to the decision to use a replacement lining made of heat shrink tube, instead of keeping the original pipe in place for a longer period, it was motivated for the following reason: indeed, if one deflates the pipe, it will shrink in diameter and separate from the surrounding concrete (a necessary condition to ensure its easy removal). Therefore, if water would be circulated within the pipe, its effectiveness would be very much decreased due to the air void in between the pipe itself and the surrounding concrete. For that reason, it was considered more viable to hook a heat shrink tube at the end of the pipe when removing the pipe. Upon pulling of the pipe, the heat shrink tube is placed into position, and the system becomes ready for pumping water. The diameter of the heat shrink tube has been selected to be slightly lower than the diameter of the cavity, allowing it to expand to the shape of the cavity as soon as water is pumped through it.

Fig. 7 shows the experimental framework protocol for the "U" shape pipe following the phases mentioned in the previous section for a diferent geometry of concrete and shape of the pipe. The geometry of the concrete block is slightly diferent in order to accommodate a "U" turn in the pipe configuration, having hence been increased to 50 cm $\times$ 100 cm $\times$ 20 cm. The pipe has 3 main segments: a first inlet straight segment of 100 cm, a second "U" turn segment with circular shape of radius 25 cm (compatible with those typically observed in the layouts of post-cooling systems), and a final outlet segment of 100 cm length. The total embedded length of the pipe is now of 250 cm, as opposed to the previous 100 cm of the initial attempts reported before.

Fig. 7a, presents the positioning of the pipe over the regulating concrete and inlet/outlet connections (following the methodology mentioned in phase 1 reported before). It should be remarked that, when the pipe undergoes oil-filled pressure, it tends to straighten. In order to keep the pipe at it is position, steel nails with the height of 5 cm have been used within segments of about 30 cm along the pipe to secure the curved pipe configuration which acts as holdfast materials for the pipe. These fixation nails are not likely to represent problems for the removal of the pipe, because of the deflation that separates the pipe from the fixators. Nevertheless, this is a process to be fine-tuned/adapted in larger applications, that are likely to require a different strategy (e.g. standard rebar fixation devices to connect the pipe to existing rebars).

Then, the casting of the concrete was carried out according to the phase 2 reported before, as shown in Fig. 7b. Then, while waiting for the conventional 'setting time' to occur, the system was monitored as to make sure that the pressure of the manual oil pump system was constant, as shown in Fig. 7c. In this figure, also a cross section of the specimen is presented. Then, following phase 3, at setting time of the concrete (lasting about 6hr), the heat shrink tube was applied to replaced with the pipe (simultaneously removing the pipe while, heat shrink tube was hooked to the end of the pipe), as shown in Fig. 7d. It should be mentioned that a manual force of about 15 kg (exerted and measured in the same manner as indicated for the initial attempts) was required to remove 250 cm length of pipe from the concrete, while also pulling in the heat shrink tube. Then, the inlet and outlet of the heat shrink tube are connected to the electric water pump and a water storage tank, respectively (using convertor and clamps fastener). Finally, a successful water circulation for 4 days in the concrete system was performed, without any kind of leakage being observed (neither particle washout, as there was never contact of the circulating water with concrete).

As a final note, it should be remarked that, at the end of the cooling process, the heat shrink tube should be removed.

A relevant question to be asked upon upscaling of the methodology to the real scale would be: '*Will the forces to pull the pipe grow to extents that might endanger the feasibility of pulling and the integrity of the concrete surrounding the pipe?*'. The integrated analysis of the attempts performed in the scope of this research may assist in trying to answer such question. For that purpose, Fig. 8 shows, relationship between required force for removing pipe from the concrete versus length of the pipe. It is interesting to note that, the required force for the "U" shape pipe (when the length is increased by 2.5 times, and added friction might be expected due to the "U" turn configuration), was only 20% higher than the one needed to pull the straight and smaller pipe. Also, it is relevant that this force was a peak force necessary to start the movement of the pipe in all cases, and after such initial movements, the necessary force to pull was much smaller. This is a positive indication that leads the authors to speculate that the pulling forces potentially involved in a real-scale application might still be compatible with the means that can be affected in a construction site at a reasonable cost, and also assure that no damage is inflicted to the structure from which the pipe is being removed from. This is nonetheless something that requires further testing at real scale to be proved.

Upon the end of the experiment, a full visual inspection of the 2.5 m long cavity after removal of the heat shrink tube was made, by using a boroscope camera (JONNESWAY model AR020065) with a soft metal probe with diameter of 5.5 mm, as shown in Fig. 9, captured near its end extremity, yet representative of the entire cavity. It was noticed that, the surface was very well preserved, smooth and not exhibiting any significant pores, or any kind of large voils, thus confirming further the viability of the proposed methodology.

4. Conclusions

Post-cooling technique of concrete with embedded cooling pipes is a frequently used method for temperature control in massive concrete structures, with the final goal of mitigating the occurrence of thermal cracking. Despite its popular use, this technique has the great disadvantage of embedding the cooling pipes in concrete permanently, despite the fact that they are only really needed during the first weeks after casting. Taking into account the stated facts that can be perceived as drawbacks of these existing techniques, from the economical and sustainability points of view, the present research, has focused in proposing a new methodology based on removability of the pipes (PVC hoses) that allows the full re-use of all materials/components/equipment involved in the post-cooling process, without necessarily bringing any additional important activity or cost to the process.

This paper has laid out the principles of the method and demonstrated initial attempts to materialize it, up to a final prototype that could demonstrate, at this scale, that: (i) it is possible to remove the initially placed/positiones pipe shortly after structural setting of concrete, without causing any visible damage, even if the case where the shape of the pipe is not straight; (ii) the forces involved in the removal

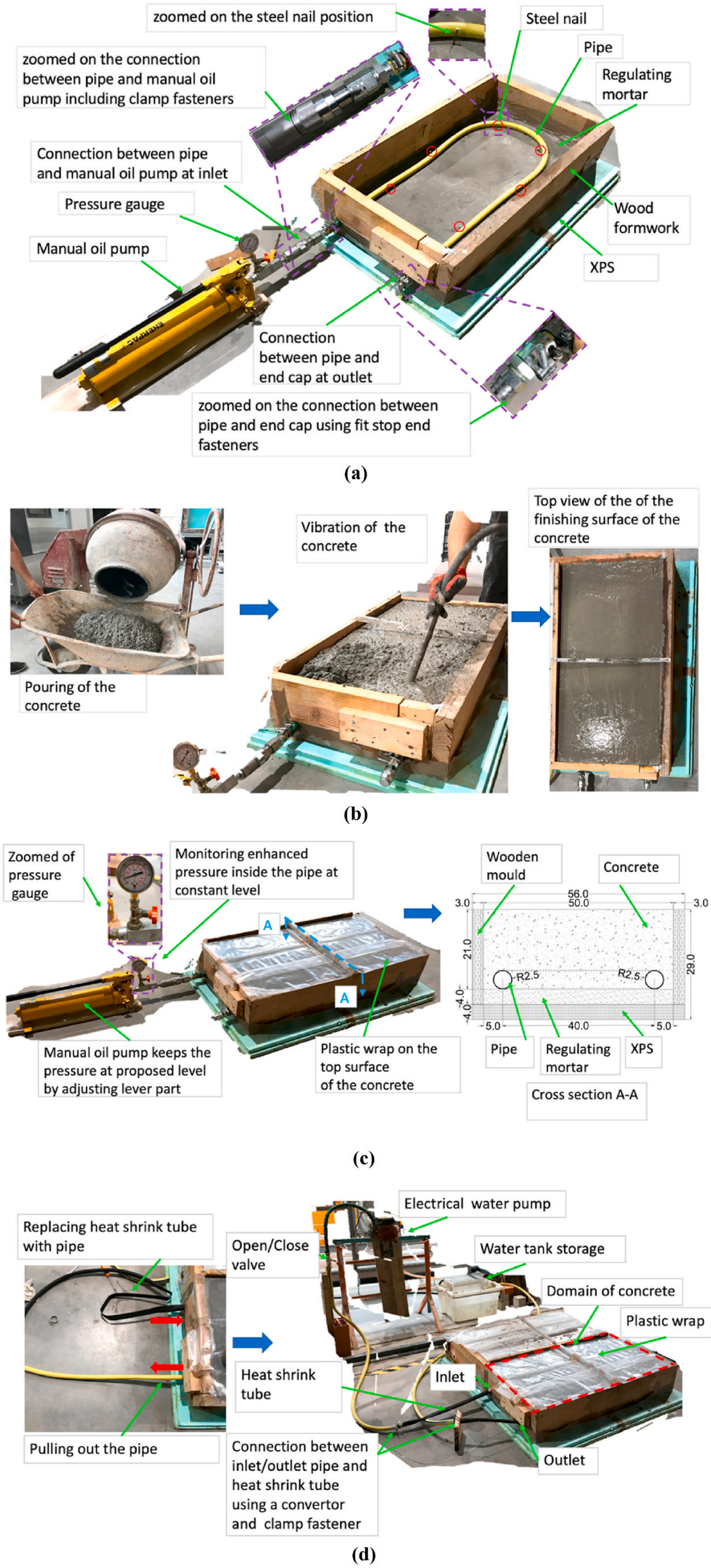

Fig. 7. Setup of the experimental test. Units: cm; (a) placement/positioning of the pipe over a regulating mortar and connection types and connections at inlet and outlet and highlighting position of the steel nails to secure and fix the pipe position before casting concrete ""; (b) Pouring, vibrating and top view of the finishing surface of the concrete; (c) Maintaining a constant proposed pressure at pipe while curing the concrete including cross section A-A; (d) Pulling out the pipe and replacing it with heat shrink tube and water circulation by pump motor and connection joints.

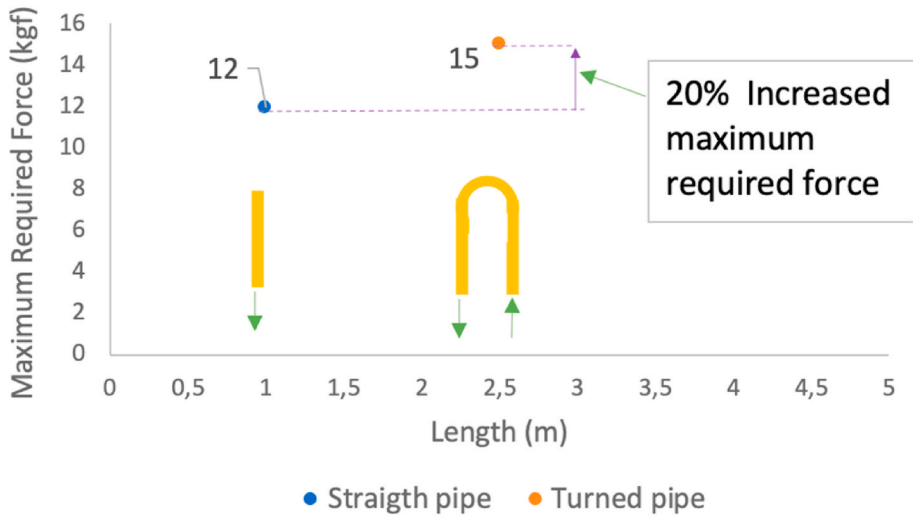

Fig. 8. Relationship between required force for pulling out the pipe and length of the pipe.

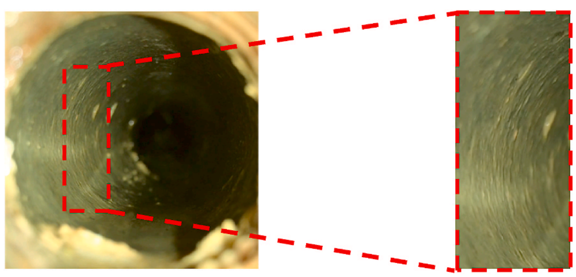

Fig. 9. View of the concrete cavity after removal of the lining sleeve with zoomed image on the surface of hole indicating smooth surface without any large voids.

are relatively small, and shall remain expectably small at real scale according to the initial tests performed; (iii) the circulation of water in the cavity generated by the removal of the pipe is made within a heat shrink tube that demonstrated adequate performance in the process of placement/positioning (being pulled in the process of removal of the pipe), without any observed risk of internal water leakage or damage to the surrounding concrete; (iv) all the materials and parts involved in the system have demonstrated their feasibility to be reused, as no damage was observed to either of them (it is inclusively noted that all the oil to keep the pipe under pressure could be retrieved without ever coming into contact with concrete).

Based on all the findings obtained at this 'proof-of-concept' stage, the authors consider that the grounds for attempting a real-scale test are laid, particularly in order to verify the practical capacity for heat removal in a structure large enough to cause significant temperature elevations, and also to verify whether the forces involved in the pull out process of a full-length cooling hose remain within feasible limits from a practical point of view. Furthermore, other options other than oil pressure to assure the necessary diameter change of the initial pipe can be considered (e.g. shape memory alloys; active internal structure of the pipe). In any case, upon demonstration of feasibility of the method at a larger scale, the method could be considered apt to generalized application with significant sustainability advantages, bearing into account the tons of material that currently are being wasted (i.e. embedded into concrete with limited, or at least hard, conditions for recycling) in currently post-cooling systems.

Author declaration

I herby confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. I further confirm that the order of authors listed in the manuscript has been approved by all of us.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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