Use of the MRI technique to study concrete and FRP reinforced concrete behaviour

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ABSTRACT: This work is one of the first attempts to apply the MRI technique in order to study the behaviour of concrete and reinforced concrete. As this technique allows the three-dimensional complete visualization of the materials, the experimental approach chosen was to visualise the specimen during laboratory trials. The AFRP reinforcement was used as example of application. The used laboratory trial was basically the compression test on cylindrical specimen of concrete and confined concrete. The main goal was to verify the possibility of applying this technique through some examples. Due to the physics functioning of the machine the study of the behaviour of reinforced concrete can only be done using non-metallic reinforcement. Despite some difficulties occurred during the investigation, the results clearly show the applicability of this tool to obtain the researched information. The evaluation of the above mentioned difficulties and their partial solution are certainly interesting for developing a future method of investigation.

INTRODUCTION

The concrete is a cement-conglomerate made mixing aggregates and cement paste in adequate proportion. The interaction of these materials with their different properties, confer to the concrete its physical, chemical and mechanical characteristics determining its final behaviour. The study of concrete behaviour, due to its heterogeneous characteristics, requires an experimental approach that allows the direct evaluation of the various internal phenomena, as well as the assessment of possible analytical and numerical patterns proposed in the literature. The most complete experimental approach is the visualization of the specimen through a non-invasive instrument during the laboratory trials. Different instruments and technologies have recently been used to achieve this aim with not valuable and useful results. In this study, here partially reported[5], the use of the MRI technique in this field of the research has been tested. As this is the first application of this tool for concrete, a large investigation has been necessary on the physical principles of the functioning of the instrument, especially regarding the usability of the materials. Here below the most interesting aspects of this study are reported with some representative results of its possible application.

MAGNETIC RESONANCE IMAGING (MRI)

The MRI technique obtains images by decoding a magnetic resonance signal. Its first applications occurred in the medicine field, where it was developed for diagnostic purposes of some diseases. The use of this technique allows the direct and non-destructive visualization of

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static and dynamic phenomena of fluid transport in porous media. For this reason its development has recently found even more application in different fields of the research. The magnetic resonance works thanks to the simultaneous application of a magnetic field and a radio-frequency pulse. The magnetic field produces an alignment of the rotation of the hydrogenous nucleus that are present into the materials. At this point the application of the radio-frequency pulse excites the system suddenly changing the direction of these rotations. During the time necessary to return in the equilibrium state, the system generates a recordable signal. This signal is proportional to the proton density of hydrogenous and therefore, indirectly, to the local water content. Applying magnetic gradients in every direction the signal acquires spatial discrimination. The visualization of the elements inside the object occurs thanks to the distinguishing of the materials according to their water content. Due to the presence of the magnetic field, the signal acquisition requires non-magnetic elements inside the sample. Time and methods used to acquire the signal, as well as gradients and applied magnetic field, can remarkably change the possibility to visualize the object. Their calibration, for every kind of investigation, makes the MRI technique very flexible. The knowledge of the physical functioning of the tool is necessary for the first approach to the experiments because it allows the identification of a certain number of factors that can influence, block or disturb the acquisition of the signal.

EXPERIMENTAL PROCEDURE

Experimental aims: The specific aim of this work is to demonstrate the applicability of this technique for studying the behaviour of concrete. It is required first, to analyse the power of this tool with concrete materials and second the definition of an experimental procedure to use this tool for studying concrete. A large phase of experiments has been done to check the visibility of each material in order to choose the concrete mix design. The study of the behaviour of concrete, using the visualization methods, needs the analysis of two main elements:

- The internal structure
- The fractures (and fracture propagation)

The visualization of the internal structure on the images requires the capacity to distinguish every component of concrete. In order to correctly obtain this visualization it is required: the homogeneity of each material that forms each component and the contrast between different components. The best researched contrast is to obtain three different shades of grey thus three different water content. The water inside the fractures should give white (that corresponds to the maximum signal) and the absence of water inside the aggregates should give black (no signal). To complete the visualization of the structure the matrix should allow a sufficient water content to appear grey on the images. Besides of this, the filling of water inside the fracture requires a permeable matrix. The interest to visualise the fractures is bigger, as smaller is their first visible size. The micro-crack visualization (100-200 μm) allows the study of their growth and propagation inside the specimen (fracture process). The fracture process is the key point to understand the internal mechanisms that govern the mechanical behaviour of concrete. The precision of this tool is function of the experimental procedure, as well as of the used materials. Its correct evaluation requires further investigation. The evaluation of the results and the phases of the investigation could lead to define a standard experimental procedure necessary to carry on a real analysis of concrete behaviour. This procedure should allow repeatable, reliable and representative experiments.

Specimen: The choice of the specimen dimension, for this kind of experiments, must follow two important criteria. The first one is meant to increase the resolution of the visualization in order to decrease the minimum size of visible fractures. The image resolution is limited by the software available with the MRI machine. Thus to increase the resolution of the objects is required to decrease the size of the specimen. The second criterion is to limit the influence of the scale effects on the specimen behaviour and involves a limit to the possible reduction of its dimensions. The importance of this second criterion grows moving the application to the visualization of reinforced concrete behaviour (or doing more complicate tests on the materials). The application of the MRI technique to study the reinforced concrete is possible only using non-metallic reinforcement, which, for example, can be made in FRP. During the investigation the visualization of the concrete behaviour has been done scanning some cylindrical specimen tested in compression. The dimensions of the specimen were 30 mm of diameter and 45 mm of height. The visualization of the behaviour of the FRP reinforcement was done using the same kind of specimen reinforced by confinement with AFRP spirals appropriately manufactured. The geometry of the AFRP spiral has been chosen using practical, experimental and analytical considerations in order to give the researched confinement effect. For these experiments the spirals were put inside the concrete, as well as outside, in order to isolate their action. A secondary aim could be seen as highlighting the power of this technique for studying FRP reinforced concrete.

Materials investigation: The concrete mix-design is one of the most important aspects of the organisation of the experiments because the MRI technique requires excluding all magnetic elements inside the specimen. For this reason a preliminary phase of investigation was done verifying the visibility of each useable material. Some of the experimental results show the disturbance caused by these magnetic elements. In Figure 1 are shown some of the images obtained scanning the available aggregates. The aggregate chosen was the limestone because it presents, besides a good visualization, appropriate stiffness, shape and characteristics of the surface.

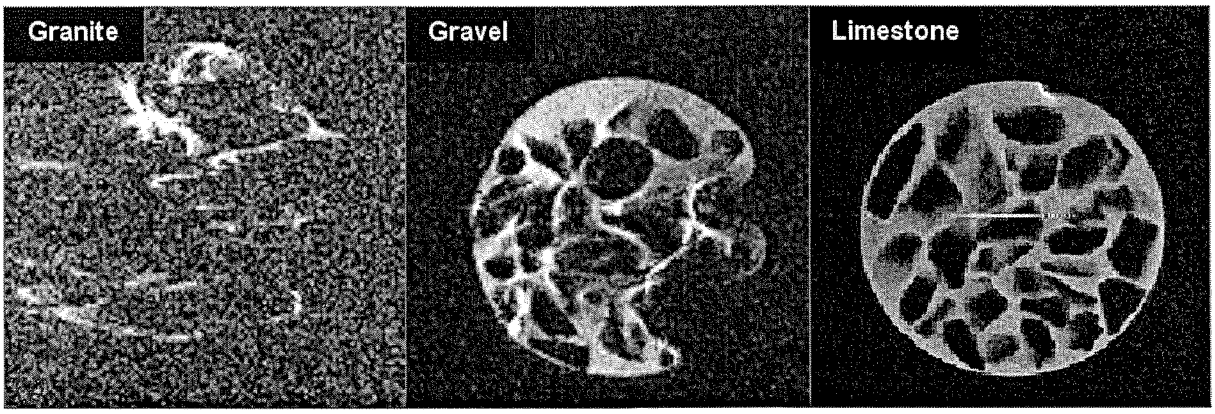

Figure 1: Example of aggregates visualization

In Figure 2 are shown the images of some possible matrix. In spite of a good saturation of the matrix the cement does not allow the signal generation[6]. The image of the cement ordinary Portland shows a feeble deformation if compared with the image of the sample (geometry of the holes and their relative distance). It is probably caused by an excessive presence of

6 This limit is function of the power of the MRI machine used and more in general of the experimental procedure

paramagnetic centres (principally Fe_2O_3 that is present 2-5 %). Instead of this the content of these centres in the white cement is evidently reduced (probably $Fe_2O_3 < 0.3$ %) and it allows the correct acquisition of the images by the MRI machine. The physic characteristics of this kind of cement are similar to the characteristics of the ordinary Portland thus the manufacturing of the specimen proceed with this matrix.

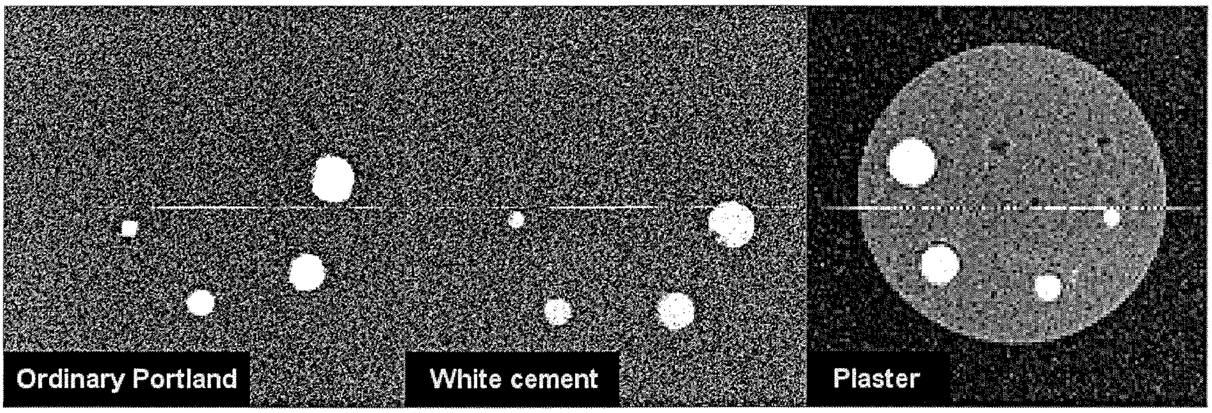

Figure 2: Example - matrix visualization (with holes full of water)

The maximum diameter of the aggregates has been chosen proportionally with the dimension of the specimen considering that a big reduction could lead to a more fragile behaviour of concrete making more difficult the control of fracture propagation during the experiments. The minimum diameter of the aggregates must be chosen sufficiently bigger than the resolution of the images in order to allow its clear visualization. The resolution used for the images was 256 pixel by 256 pixel with a field of view of 40 mm by 40 mm. The specimen is completely inside the field of view and the dimension of the pixel corresponds approximately to 150 μm. The concrete mix-design used for manufacturing all specimens is shown in the Table 1.

Material	Dimension	Quantity	% in weight
-	mm	g	%
Sand type B	1.18 - 0.60	280	28
Limestone	4.00 - 2.36	320	32
White cement	-	260	26
Deionised water	-	135	14

Table 1: Concrete mix-design used

Phases of the experiment: Due to the physics of the instrument the water must be seen as the indirect way to visualize the materials. The set-up of the experiment should allow the saturation of the matrix and the controlled filling of water inside the fractures (it should happen at least before each phase of scanning). To achieve these conditions some experiments with concrete specimen have been done trying to experimentally find out the best procedure (different procedures can be used). If the fractures are internal to the specimen their visualization is allowed by the possibility to filter the water through the cement. This is often the case of the micro-fracture. The impossibility to organise all phases of the experiments inside the MRI machine involves their execution in consecutive phases. When the specimen was tested to the chosen level of fractures (using in this case the compression test) they were put under water and in vacuum for a reasonable time. The vacuum speeds up the process of saturation and filling of the water inside the fractures. After this, the specimen was scanned with the MRI machine. The repetition of these phases for different level of load with the same specimen allows the visualization of the fracture propagation. The procedure, used to allow the saturation and the filling of the water, has to be verified and controlled during the experiments. Future investigations must be addressed to define the time required to correctly execute all phases. The time necessary to acquire a three-dimensional image with this kind of material and instrument are quite long (9 hours each). However, the instrument allows the acquisition of a set of bi-dimensional images in a shorter time (18 min) with the same resolution. For some kinds of experimental researches the bi-dimensional visualization could be sufficient to understand the investigated phenomenon. In any case a bi-dimensional image is suitable before to launch the three-dimensional acquisition sequence.

RESULTS

The obtained experimental results do not allow a complete and correct analysis of the investigated phenomenon, but they present an interesting result to evaluate the power of the MRI technique in this specific field of application. The images present some defects, mainly due to some practical problems occurred and not totally solved during the research of an experimental procedure. Different ways have been found to solve these problems and the next investigation will certainly give better and complete results. The research of the fracture propagation inside the specimen during the compression test needs to find out which are the levels of load, more interesting for this phenomenon. The literature predicts the production of the first micro-cracks at 40 percent of the ultimate load. These fractures are probably smaller than the dimension of the pixel for the used resolution. The impossibility to practically do the compression test with accurate displacement and load control, for this kind of specimen, limits the analysis of the results regarding the fracture propagation. However, an example of images of fracture propagation is shown in Figure 3. The effective levels of load have a remarkable uncertainty degree (they are near to 50, 75 and 100% of the ultimate load respectively). The various levels of load in the images represent different slices of the object thus it is not possible to follow the growth of each single fracture. The comparison between the results of plain and confined concrete highlights the added confinement effect. An example of these visualizations is shown in Figure 4.

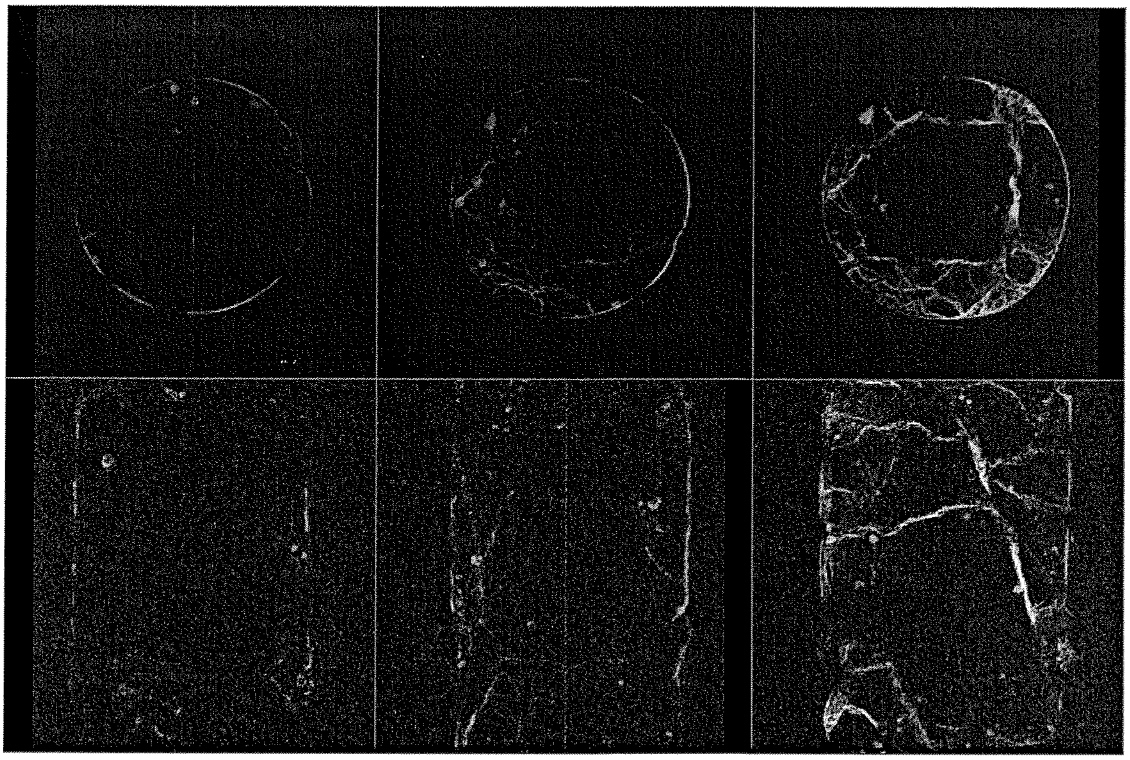

Figure 3: Confined concrete – Fracture propagation

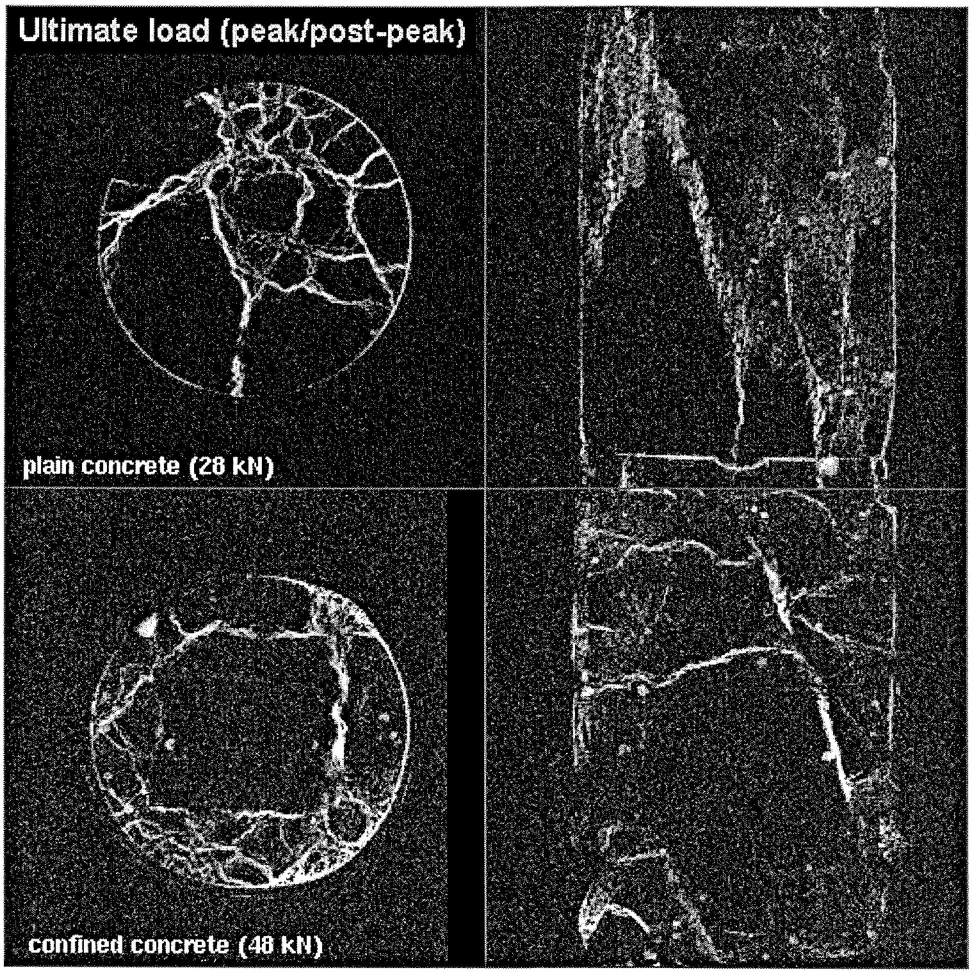

Figure 4: Ultimate load for confined and plain concrete

The general limit of quality and reliability of the images is given by the combination of the following factors: resolution (chosen), precision of the instrument (unknown) and quality of the set-up of the experiments (difficult to evaluate). The analysis of the three-dimensional images can be done using a set of cross-section of the object or using three-dimensional reconstruction software. Acquiring a set of three-dimensional images it is possible to see shape, geometry, surface and development of these fractures during the most important steps of a laboratory trial. The relationship between the degree of fracture and the level of load during these stages can clarify the concrete behaviour and lead to some empiric formulation. The three-dimensional reconstruction of the confined specimen (represented in Figure 3) at the ultimate stage of load is shown in Figure 5. The above mentioned information, contained in the images, can be related to the load condition and the energy absorbed during the engineering tests.

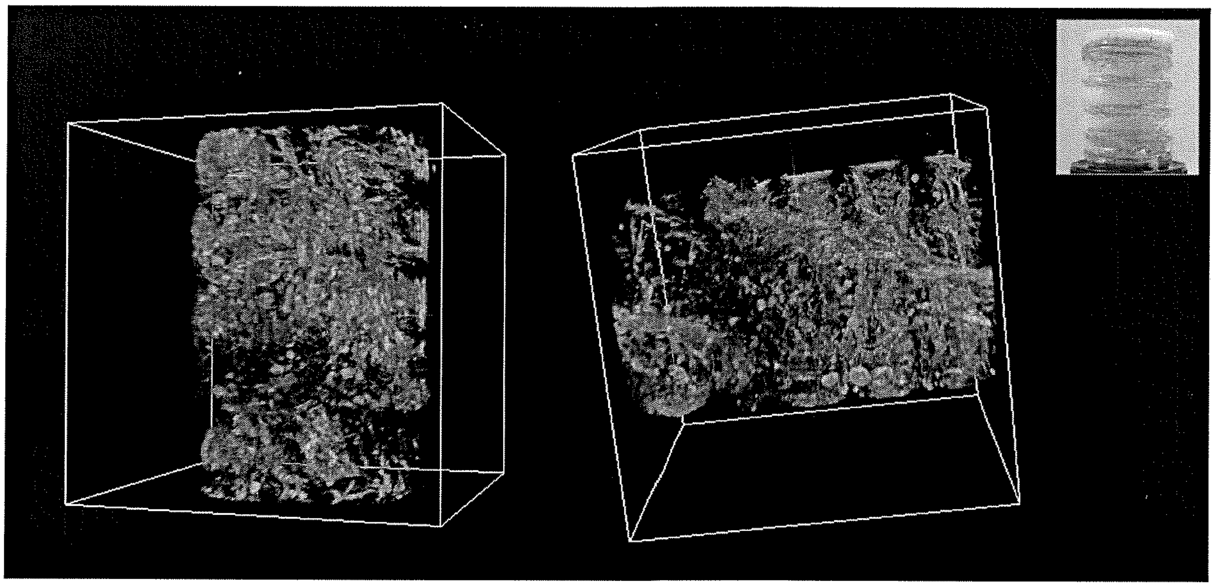

Figure 5: Confined concrete – Three-dimensional reconstruction at the ultimate load

The development of a simple post-processor software could be of help for the analysis of the data contained into the images, allowing also the reconstruction of the fractures propagation during the trials. The impossibility of viewing the concrete structure, on the images representing the fractures, makes the fractures analysis easier because their individuation by this instrument is immediate and unmistakable. The visualization of the inner structure would allow to further analyse the behaviour of the material (relationship between structure and fractures, control of the quality of the produced material and digital reconstruction for checking numerical and analytical model for concrete). If some of these information are requested, for specimen prepared in laboratory, the MRI technique allows to obtain an image of the inner structure of the material from a scanning performed during the setting and the hardening of concrete. During this phase, the high content of water inside the material makes the tool more powerful. An example of such an application is shown and summarized in Figure 6, that represents the result of a pull-out test carried out with a little AFRP rod (the rectangular object on the left is a reference system used to overlap the images). The images overlap allows to identify the various kinds of fractures (bond fracture, fractures through the matrix or the aggregates), which are the fundament for evaluating the behaviour of the micro-structure. The visualization of the two researched information (structure and fractures) in two different images makes the analysis easier and immediate. This analysis can be easily made automatically and added to the analysis of the fracture propagation.

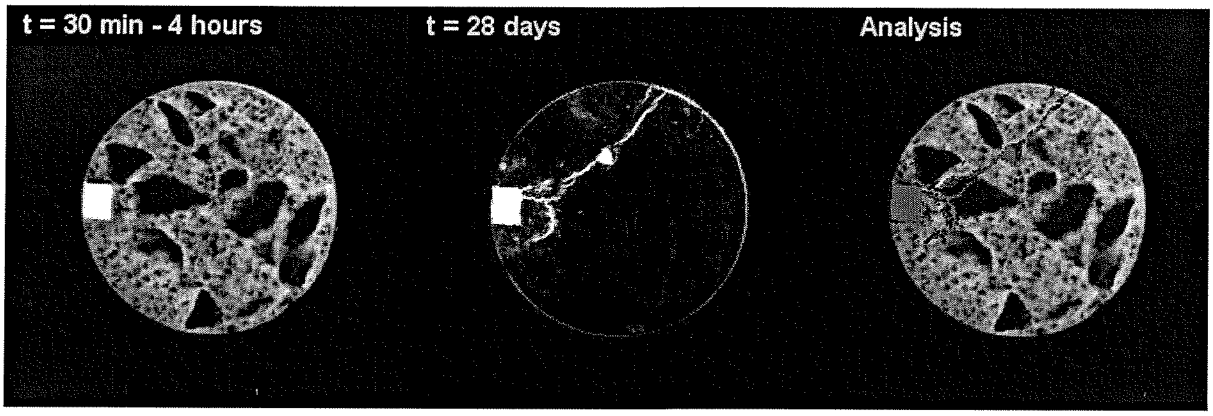

Figure 6: Complete approach – structure visualization and fracture analysis

The two researched information are very different and generally they require different degree of precision and, indirectly, of resolution. Due to the high contrast obtained, the necessity to increase the resolution is not so important as for other tools. This allows to proceed using bigger specimen reducing the problem of scale effects.

CONCLUSIONS

The work done gives the necessary information to apply the MRI technique to study the behaviour of fracture in concrete. Of particular interest is the preliminary study addressed to the materials analysis that allows to correctly choose the mix-design of concrete in order to maximise the results obtainable by using this instrument. Despite some defects, the experimental results, here reported, clearly show the power of the MRI technique for this topic. The binary characteristic of the fracture visualization allows their direct and unequivocal individuation. This process of analysis can be easily automatically done by software. Despite some important choices, made for the specimen manufacturing, the application of this technique for every kind of concrete is not totally excluded but it requires more investigation. Further works are required to define a standard experimental procedure in order to allow the control of all phases of the experiment (from the specimen manufacturing to the control of data analysis). This procedure will easily allow the design of some experiment addressed to analyse the concrete behaviour. The possibility to obtain two different information in two different images, gives to the application of the MRI technique a big advantage, compared with other tools, especially looking at the possibility to automatically do the data analysis. The flexibility of this technique allows to find out the possible answer to different requirements of every kind of investigations. The possibility of visualising the structure using consolidated concrete, eventually with fractures, is not totally excluded at the moment, but it seems not necessary to analyse the investigated phenomenon. In this direction it could be useful to increase the power of the instrument, as well as the concrete mix design adding something to the matrix in order to increase his water content.

ACKNOWLEDGEMENT

The authors wish to acknowledge the European Commission for funding the EU TMR Network "ConFibreCrete". The authors wish to thank the professors G. Bartoli and S. G. Morano in the University of Florence for their cooperation and for having allowed the development of this project in Cambridge University. A special thanks is for all people that work in the laboratory used (HSMLCM and Engineering Department Laboratory of Cambridge University) for their interest, their friendship and disposability.

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