Fracture Mechanics of Concrete and Concrete Structures -
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Investigation of porous concrete through macro and meso-scale testing

A. S. Agar Ozbek
Delft University of Technology, Delft, The Netherlands

J. Weerheijm
Delft University of Technology, Delft, The Netherlands
TNO Defence, Security and Safety, Rijswijk, The Netherlands

E. Schlangen
Delft University of Technology, Delft, The Netherlands

ABSTRACT: In designing a porous concrete, containing a high volume of air pores, the effects of its meso-scale phases on its macro level properties have to be known. For this purpose, porous concretes having different aggregate gradings and cement paste compositions were investigated through macro-scale strength tests. The tests showed that aggregate grading had a predominant effect on the properties of porous concrete in comparison with cement paste composition. Replacing cement by silica fume even slightly lowered the strength values of the porous concretes which was explained by the presence of agglomerates. Meso-scale tension tests were also conducted to determine the tensile strength of the ITZ. The tests at the two different scales revealed that, even though the ITZ phase did not become weaker with the presence of silica fume with the inclusion of agglomerates, the strengths of macro-size samples were lowered due to the bulk cement paste phase being degraded.

1 INTRODUCTION

Porous concrete is a special type of concrete that incorporates about 20-25 percent meso-size air pores. In order to attain the porous structure, both its mixture design and the casting procedure have to differ from normal concrete. Namely, the aggregates are gap-graded or in one standard size range, the cement paste content is highly decreased and compaction in layers is essential during casting due to the very low workability of the mixture (Ghafoori & Dutta 1995). Therefore the widely known effects of some factors like adding mineral admixtures or the changing the aggregate grading on normal concrete may vary when porous concrete is of concern.

Within the scope of a project on designing a cementitious material that fractures into small fragments when exposed to impact loading, while having a sufficient performance in terms of static properties, different types of porous concretes were investigated. Because the pores are essential for the required dynamic performance of the material, in the process of optimizing the mixture components, the main focus was to enhance the static strength properties while maintaining the high air pore content. The objective of the current study, that presents some results from the project, is to evaluate the effects of parameters such as the grading of the aggregates and the presence of silica fume in the porous concrete application.

Although the enhancing effect of silica fume on the mechanical properties of concrete is well accepted, there is controversy as to whether the enhancement is due to its effect on the ITZ (Cohen et al. 1994) or in large part because of the improved strength of its bulk cement paste constituent (Cong et al. 1992). The situation in porous concrete is slightly more complicated and less known due to its mixture design and the distribution and relative amounts of its phases as it will be explained in the discussion of the experimental results. The influence of changing the aggregate grading is also different for the same reasons.

To be able to understand the fracture mechanisms of a composite material, the behavior of its different phases should also be investigated separately. Data on the mechanical properties of the interfacial transition zone is therefore essential to be able to fully understand the global behavior of normal as well as porous concrete. Because of the complex geometry and high heterogeneity of porous concrete, smaller-scale testing with a more simple geometry was highly required to be able to determine the properties of particularly the ITZ phase. There is a considerable amount of information based on microscopical studies that very clearly demonstrate the formation and structure of the ITZ. According to those studies it is not a discrete zone but a region of gradually changing microstructure. It has a significantly higher porosity especially at the very inner first 15-20 μm from the aggregate. It has preferential fracture planes because of the preferential orientation of calcium hydroxide parallel to the aggregate surface (Scrivener et al. 2004). Although its microscopic structure is now well known, there is very limited experimental data available on its mechanical properties. In order to measure the load-displacement response of the aggregate-cement bond, some testing techniques have been used. (Alexander 1993, RILEM 1996). In one of the studies on the subject, the bond strength for different aggregate types and surface roughnesses were found to be between 0.2-1.2 MPa (Zimbelmann 1985) while in another study the bond strength was around 2 MPa (Hsu & Slate 1963).

In this study, the experimental procedures that were followed in conducting macro-scale testing on porous concrete and meso-scale testing on ITZ, and the evaluation of the results at the two different scales in order to explore the mechanical properties of porous concrete are presented.

2 EXPERIMENTAL PROCEDURES

The testing was done at two different scales, namely, the macro-scale (testing the porous concrete structure) and the meso-scale (testing of ITZ, considering the size of the sample, even though ITZ is a formation at micro-scale).

2.1 *Macro-scale uni-axial tension and compression testing*

Deformation controlled macro-scale uni-axial compression and tension tests were performed on 73 mm diameter x 170 mm height and 73 mm diameter x 80 mm height cylindrical specimens, respectively. Because porous concrete readily incorporates numerous notches due to its porous nature, no notches were made on the tensile test samples. To be able to prevent the snap-back behavior, the tensile sample height was kept at 80 mm. During the tensile tests, the specimens failed at one visible major crack. The deformation measurements were made over the whole height of the samples for both the tensile and compressive tests and the average of four LVDTs were used as the feed-back signal. The loading rate was held at 1 μm/sec and 0.1 μm/sec for the compressive and tensile tests, respectively. Before testing, the weak top layer was removed while also the cylinder ends were sawn parallel and capping was applied. For the tensile test, the samples were glued to non-rotating steel platens.

2.2 *Meso-scale uni-axial tension testing*

Among the three phases of concrete, ITZ is the least known one. In numerical modeling studies, the mechanical properties of the ITZ is usually taken to be a ratio of those of the bulk cement paste phase. Although the properties of the bulk phase can be a good indication of the properties of the transition zone that forms between that phase and the aggregate, the relation is not very definite especially if there are mineral admixtures involved like silica fume that is known to influence the ITZ and bulk cement paste phase properties at different extents. Therefore, the proper material design considerations require specific knowledge on the ITZ phase itself. The composite sample for testing the ITZ was originally designed for modeling purposes i.e. in order to determine the model parameters of ITZ from a simple geometry.

A testing method to determine the mechanical properties of the interfacial transition zone has not yet been established due to the complexities of performing tests that involve ITZ which has a micro-scale thickness. As a direct way of extracting information on the tensile behavior of ITZ, displacement-controlled uni-axial tensile tests have been performed on the composite samples shown in Figure 1 using the meso-scale compression-tension testing machine in Figure 2.

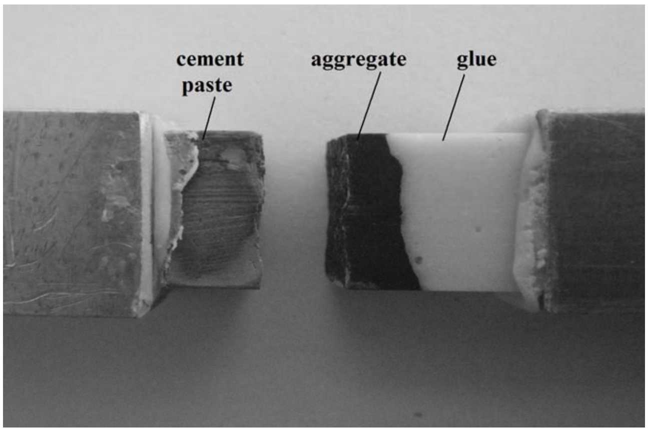

Figure 1. Meso-scale uni-axial tension specimen after the test.

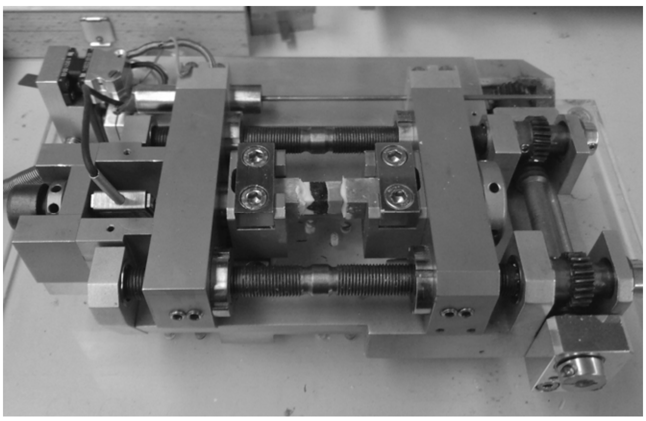

Figure 2. Meso-scale compression-tension test setup.

A systematic approach was followed to modify the geometry of the sample while different geometries have been tried. Keeping the natural surface of the crushed aggregate instead of making artificial roughness on polished aggregate surfaces, was an important feature of the samples to be able to have a more realistic ITZ structure being generated. The dimensions of the sample section were selected to be 8 mm x 8 mm taking the 4-8 mm aggregate size range of the porous concrete as reference to be able to have shrinkage conditions as similar as possible to the macro size porous concrete samples. The square aggregates were cut from the special aggregate-glue composite samples that had previously been prepared using an epoxy based glue to be able to have an as straight as possible horizontal surface on top, keeping the natural aggregate surface, while having the flat surface of the glue at the bottom. The square aggregates were then placed at the bottom of the moulds onto which 5 mm of cement paste was poured. The moulds were vibrated on a normal size vibration table. The samples were wrapped with aluminum and plastic foils and kept at 20 ºC at the laboratory conditions exactly like the macro-size samples.

2.3 *Computed tomography analysis of fractured samples*

Computed tomography is a very effective tool in examining the post-fracture properties of concrete. In conducting the CT scans, a Phoenix Nanotom X-ray computed tomography machine which can go up to a resolution of 0.5 µm/voxel, depending on the sample size, was used. In the tomography application of inspecting cracks after a uni-axial compression test, samples that are cut from the macro-size specimens can be as large as 3-4 centimeters in thickness while the sections inside the sample can be visualized with a resolution of about 23 µm/voxel (a mean filter 3 is usually applied). Because there is no need for polishing, the effect of sample preparation on the cracks that are observed is minimized compared to polished sections. In the CT image, different materials are indicated by different shades of gray according to their densities. The analysis to determine the crack development of the specimen was therefore particularly efficient and precise due to the great difference in the densities of the solid phases of concrete and air. The same method was also used to determine the meso-size porosity of the mixtures by converting the acquired image to binary and simply determining the ratio of the solid and air phases, i.e. the number of black and white pixels.

3 MATERIALS AND MIXTURES

For the macro-scale tests porous concretes with and without silica fume (P1, P2 and P3) and full samples (F1 and F2) having a higher cement paste content to fully eliminate the meso-size air pores were prepared. The w/c ratio was kept at 0.30 in all the mixtures. The compositions of the mixtures are presented in Table 1:

Table 1. Mixture compositions of the porous and full samples.

Amounts in grams	P1	P2	P3	F1	F2
Basalt 2-4 mm	-	-	2000	-	-
Basalt 4-8 mm	2000	2000	-	2000	2000
CEM I 52.5R	351	298	298	951	808
Silica fume	-	53	53		144
Water	105	105	105	285	285
Superplasticizer	1.00	1.36	1.36	4.20	5.71
Retarder	0.82	0.82	0.82	2.22	2.22

The preparation of the porous concrete was done following a standard optimized procedure of first mixing the cement with silica fume at the dry state (for the mixtures containing silica fume), and then mixing the cement paste using a hand mixer and finally mixing the cement paste with the aggregates using a Hobart mixer at pre-specified standard durations. Two types of cement pastes were produced to mix with aggregates for making porous concretes i.e. with only pc (in P1) and with 15% of pc replaced by silica fume (in P2 and P3). Very low amounts of superplasticizer, were used because a higher workability cement paste does not remain on the aggregates but leaks and accumulates at the bottom of the specimen. The same cement paste mixtures that were produced for porous concrete were also used for meso-scale specimens with very slightly higher amounts of superplasticizer. With also the addition of the aggregates, the mixtures for the macro-samples become very unworkable therefore during casting every 3 cm layer was compacted using an impact hammer. Because the duration of casting was high, a set retarder was used to have a control over the setting of cement paste to be able to have sufficient time for the compaction. The specimens were wrapped with both plastic and aluminum foils and kept at 20ºC at the laboratory conditions until their testing dates.

4 RESULTS AND DISCUSSION

4.1 *Computed tomography observations*

Before evaluating the results of the uni-axial tests, exploring the structure of porous concrete can be illuminating in getting an insight in how the material behaves. To be able to visualize their partially fractured state, the specimens (with and without silica fume, i.e. P2 and P1) are loaded under uni-axial compression until the strain levels that can be seen in the stress-strain diagrams below and then impregnated with epoxy to make the cracks more stable even though not much cutting is involved because the pieces to be cut are large. The pieces of samples that are shown in Figure 3 and Figure 4 were taken from the outer mid-height region of the specimens.

When the partially cracked sections of the specimens are observed, it can be said that even though the crack patterns seem to be generally similar to those observed in normal concrete, there are some differences.

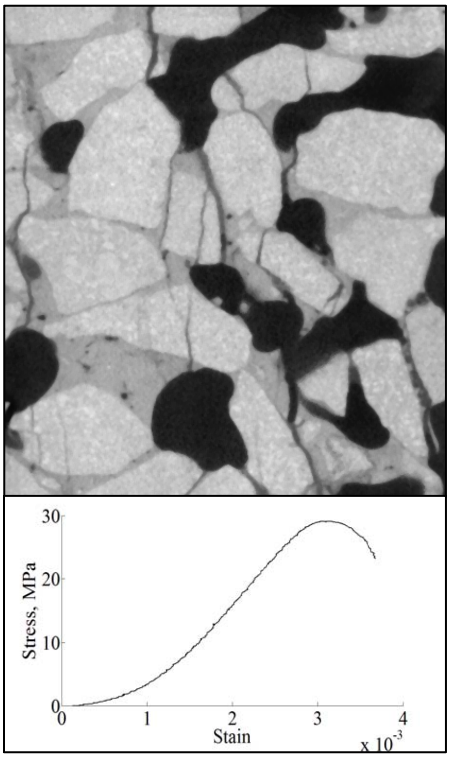

Figure 3. Partially fractured porous concrete with pc.

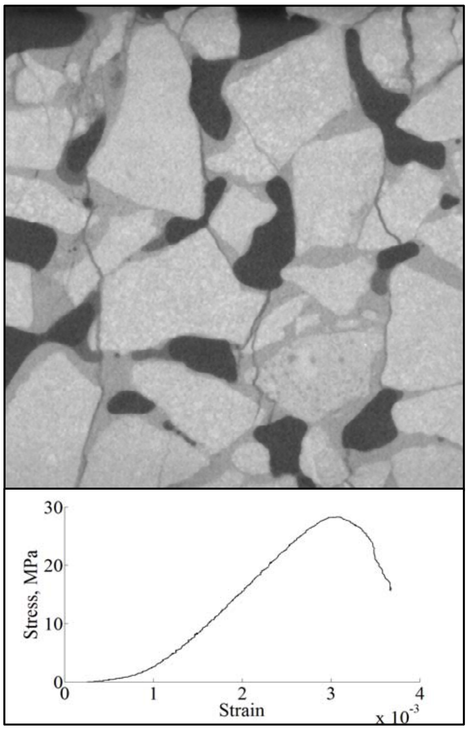

Figure 4. Partially fractured porous concrete with 15% silica fume and 85% pc.

It is expected that stress concentrations form at the contact locations between the aggregate particles like in normal concrete. In porous concrete, due to the aggregates being mono-sized, there are a very small number of only coarse aggregates present. Therefore, the amount of contact regions between the aggregates compared to the complete aggregate surface is very much lower than it is in normal concrete. Although the failure seems to predominantly initiate from the debonding cracks close to the aggregates and the subsequently propagating tensile cracks parallel to the direction of loading like in normal concrete, the cracks are sometimes forced to propagate into locations guided by the geometry of the skeleton structure. Because there is only a very a small portion of ITZ and bulk cement paste connecting each aggregate and the rest of the matrix is not existing, the cracks have to propagate according to the geometry of the phases that are physically present; which is not the case in normal concrete where there is the presence of the whole matrix material along with the inclusion of fine aggregates.

When investigating the effect of ITZ or bulk cement paste phase compositions e.g. the effect of adding a mineral admixture like silica fume to the cement paste, the amount of those phases that are actually in function being considerably low should therefore be considered. The presence of the very high percentage of (about 25%) meso-size air pores is an additional cause of heterogeneity in the structure along with the added effect of the porosity itself not being homogenously distributed in the section introducing anisotropy according to the direction at which the compaction is performed. When the two sections, one containing silica fume and the other having only pc, are compared it can be said that in the one with only pc the cracks seem to be located slightly more at the ITZ region than the other sample however, observation of the sections from only one sample from each mixture is not sufficient to draw a reliable conclusion.

4.2 *Macro-scale uni-axial tension and compression test results*

Achieving very high compressive and especially tensile strengths is not possible for porous concrete due to the presence of high air content. Because the pores are essential for the required dynamic performance of the material, in optimizing the mixture components, the main focus was to enhance the static strength properties while maintaining the meso-size air pores. In this study, the influences of the aggregate grading and the cement paste composition on the mechanical behavior of porous concrete were investigated. The representative compressive stress-strain curves obtained for porous concretes with and without silica fume along with full samples are presented in Figure 5 and Figure 6 showing also the mean strength values of four samples. The representative tensile stress-strain curves of porous concretes with also the mean strength values of four samples and fracture energies are presented in Figure 7.

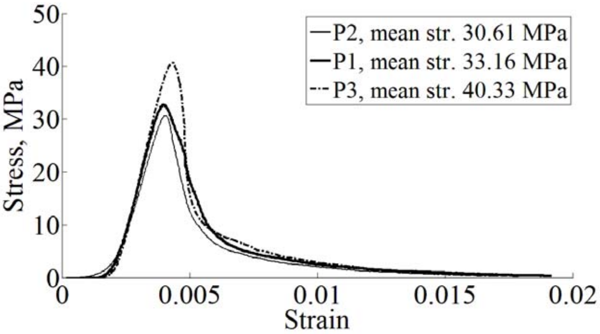

Figure 5. 56-day uni-axial compressive tests of porous concretes.

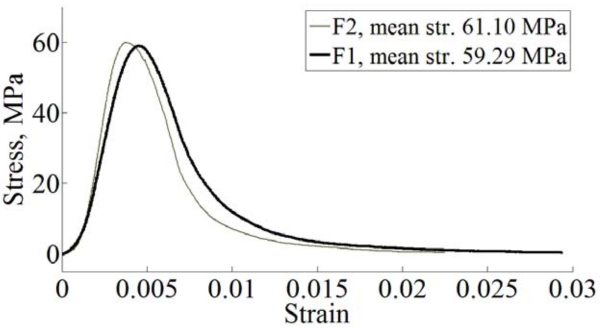

Figure 6. 56-day uni-axial compressive tests of full specimens.

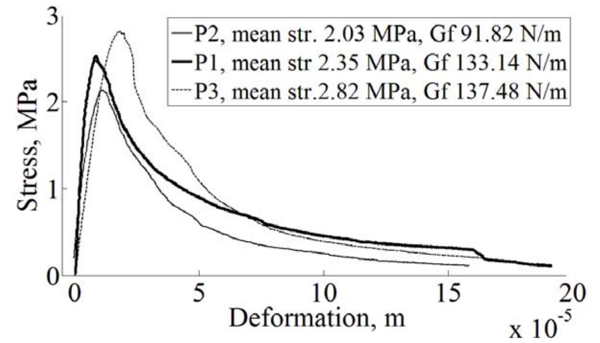

Figure 7. 56-day uni-axial tensile tests of porous concretes.

In both the compressive and the tensile tests of the porous concretes, the mixture with the finer aggregate grading of 2-4 mm showed a significantly better performance which was due to having more contact points of aggregates along with having a more refined pore structure even though the total volumes of porosity were the same. Experimental results clearly revealed that the aggregate grading and therefore the pore size distribution had a predominant effect on the properties of porous concrete in comparison with cement paste composition. The substitution of 15% of cement by silica fume, does not have a significant influence on the compressive strength of porous concrete considering the mean values and the representative curves. As previously explained using the CT scan images, a very drastic effect was not expected from the slight variation in the cement paste composition. However, opposite to the direction of what was expected, the compressive strength performance of porous concrete was negatively affected by the presence of silica fume. The compressive/tensile strength ratio is always higher in porous concrete (about 14 for all porous mixtures) compared to normal concrete. The slight decreasing effect of silica fume was also valid for tensile strength and even more noticeable in the fracture energy values. The physical explanation of this can be better made by the CT scans of the meso-scale samples (at the resolution of 46 μm/voxel) in which some agglomerates were detected in the cement paste with silica fume especially farther from the aggregate surface. The largest agglomerates measured were at the scale of 240 μm.

The agglomerates that are readily present in silica fume in dry powder form break down only partially during normal concrete mixing and remain in that form in the paste (Diamond 2006). In the porous concrete application, even though the silica fume and cement were first mixed in the powder form in a closed container by also adding steel balls to shatter the clusters and then thoroughly mixed with water, the agglomerates could not be fully eliminated. This can be explained by the very low percentage of superplasticizer used. Because the cement paste made for the porous concrete production has to be very viscous to facilitate the homogeneous distribution of the paste in the mixture, the superplasticizer used has to be very limited. Therefore the dispersion of silica fume in between the cement particles is not fully attainable (Toutanji & El-Korchi 1995).

Agglomerates that remain clearly cannot participate in the expected filler and pozzolanic effects also because agglomerates have different reaction products than fine silica fume particles (Diamond 2004). This may also be one of the reasons for the very contradictory results in the literature on the effect of silica fume. The non-agglomerated portion of silica fume is surely in function which was better demonstrated by the meso-scale tests conducted on samples having silica fume that will be explained in the coming paragraphs. Therefore, there is not a very significant effect of silica fume in the results probably due the effect of fine silica fume particles compensating for the effect of the agglomerated ones. The effect of agglomerates is expected to be more on the bulk phase which was also better understood after the meso-scale tests.

The full samples with silica fume show a slightly better performance. A slightly higher peak value of the silica fume mixture can be explained by the fact that as the cement paste content of the mixture is increased, the amount of both the bulk and the ITZ phases that are in function increases. As also seen in the CT scans of porous concrete, the amount of contact regions of aggregates, and therefore the fractions of ITZ and bulk phases under stress are very low. Hence, the slight increase in the peak of the full specimens does not mean that this is the effect of only the bulk portion being increased. The enhancement of the ITZ with the addition of silica fume is also more effective as the porosity of the section is decreased. The slight increase in the superplasticizer used in the full samples compared to the porous ones can also have a positive effect on the dispersion of silica fume particles. Therefore, the results of the full specimens do not fully explain the effect of silica fume in porous concrete.

4.3 *Meso-scale uni-axial tension test results*

Meso-scale tests were required to explore the ITZ phase of porous concrete more precisely. The preliminary tests were performed to investigate whether the load displacement data on ITZ is achievable using this specimen and the experimental configuration. The testing was done at the loading rate of 0.1 μm/sec which was the same as the loading speed at the macro-scale tension tests.

In all of the samples tested the failure occurred in the immediate vicinity of the aggregate which can be an indication of the failure taking place at the ITZ. Therefore, the peak load that is measured can be used to determine the tensile strength of the ITZ phase. Acquisition of the complete load displacement response was not possible during testing because of the snap-back behavior immediately after the peak. Therefore, the descending branch could not be captured. Some representative preliminary results of tests are collectively presented in Figure 8 and Figure 9.

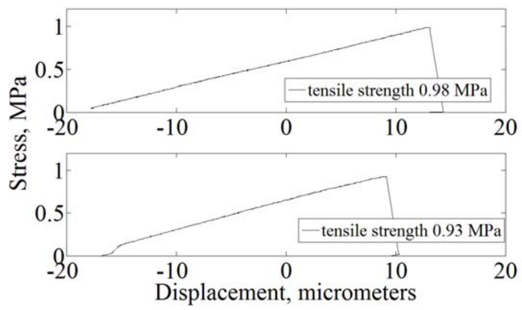

Figure 8. Meso-scale test results of cement paste-basalt aggregate interface.

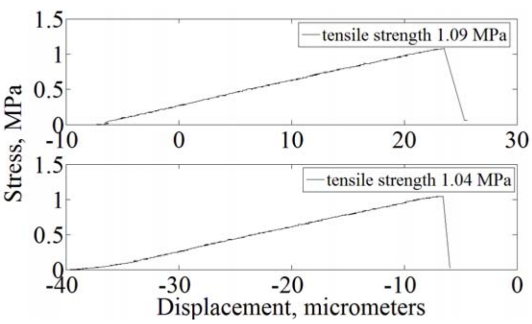

Figure 9. Meso-scale test results of cement paste + silica fume paste – basalt interface.

It should also be noted that the scatter was quite high among the results which can perhaps be partially lowered by producing more standardized specimens. An ITZ tensile strength about 1 MPa was measured in the tests while cement pastes with 15% silica fume had very slightly higher values compared to the ones without silica fume. This information can be used to better interpret the porous concrete data showing that the ITZ phase is not the reason behind the slight decrease in the compressive and tensile strengths of porous concretes with silica fume. Even though the agglomerates were identified at the CT scans of the small-size samples, the ITZ phase does not become weaker with the presence of silica fume which means that the bulk cement paste phase is affected more and has less strength than the paste without silica fume.

The stiffness information cannot be extracted from the current data because the stiffnesses of the other components present in the composite sample, namely the aggregate, the bulk cement paste and the glue are also involved. However, this testing configuration can be used to determine the stiffness of the ITZ because the ascending branch of the stress-strain curve could precisely be captured. The stiffness of the ITZ is planned to be determined as a further study with the same type of specimens using a simple series model for E, for which the stiffnesses of the other three components will also be determined separately. To be able to have a better approximation of the stiffness of the ITZ, the volume percentages of the other components will be kept as low as possible so that they are comparable to that of ITZ.

5 CONCLUSIONS

Based on the experimental results obtained in this study, the following conclusions are drawn:

Experimental results clearly indicate that the aggregate grading and therefore the pore size distribution had a predominant effect on the properties of porous concrete in comparison with cement paste composition. With decreasing aggregate size, an increase in both the compressive and tensile strengths was attained. Compressive and tensile strengths of 40.33 MPa and 2.82 MPa were reached, respectively. The contribution of silica fume to the mechanical properties of porous concrete was not significant as it even slightly lowered both the compressive and the tensile strengths measured which was explained by the presence of agglomerates that were detected in the cement paste.

The preliminary results of the meso-scale tests verify the potential usefulness of this testing configuration in studying the properties of interfacial zone between the aggregate and cement paste phases. The tensile strengths of two different types of ITZ structures were measured for this study. This testing configuration can also be used to determine the stiffness of the ITZ because the ascending branch of the stress-strain curve can precisely be captured. To be able to extract information about the ITZ stiffness, the stiffnesses of the different components of the sample should also be measured separately.

In all of the small-size samples tested the failure occurred in the immediate vicinity of the aggregate which was also confirmed by microscopic examination. Therefore, the failure takes place at the ITZ and the peak load that is measured can be used to determine the tensile strength of the ITZ phase which was measured to be around 1 MPa; while cement pastes with 15% silica fume had slightly higher values compared to the ones without silica fume. This also showed that even though the ITZ phase does not become weaker with the presence of silica fume with the inclusion of agglomerates, the compressive and tensile strengths of porous concretes having the same composition of cement paste were lowered which can be attributed to effect of bulk cement paste phase being degraded. This can partially be prevented by a more intense and prolonged dry mixing of the cement and the silica fume. Wet mixing of the powders with water and superplasticizer is not a process that can be very effective on eliminating the agglomerates because of the very low amount of superplasticizer being involved and hence the mixture being very unworkable. A more effective and long duration dry mixing can be expected to lower both the amount and the size of agglomerates that remain which can also be presumed to augment the contribution of silica fume to the mechanical behavior of the material.

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