THE POTENTIALS OF POROUS CONCRETE FOR BALLISTIC PROTECTION

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ABSTRACT

A special porous concrete has been developed by the Delft University in collaboration with TNO. The concrete has a static compressive strength of 45 MPa. It fragments at impact into small size debris relative to reference concrete. The porous concrete was developed at laboratory scale and tested at small scale. In collaboration with the Military Science faculty of NLDA a procedure was developed to upscale the production. Panels of 0.5m x 0.5m x 0.10m were produced at slightly lower strength than realized at lab scale. These panels were used to investigate the ballistic performance of the porous concrete. The ballistic resistance proved to be comparable to that of reference concrete. The instant crushing feature of the concrete causes additional damage at the front side but the damage zone was still limited in size. Spalling at the rear side proved to be limited in comparison to the reference normal concrete. To further improve the ballistic resistance of the porous concrete, it was infiltrated with a polymer. Tests showed a considerable improvement of the penetration resistance, relative to the non-infiltrated porous concrete.

The paper first summarizes the characteristics of the porous concrete developed at lab scale. The ballistic test data are presented and analyzed. The ballistic response mechanism of the porous concrete is compared with the mechanism in normal concrete. From this analysis the alternative of filling the pores emerges. Finally the paper presents the initial ballistic results for the infiltrated porous concrete.

KEYWORDS

Porous concrete, ballistics, experiments, protection, small calibre, material development, polymer filled concrete.

INTRODUCTION

Porous concrete is a special type of cementitious material composed of gap-graded aggregates assembled by the cement paste layers partially being in contact [Yang, 2003; Ghafoori, 1995]. Due to its high meso-size air pore content, the fragmentation behavior of porous concrete under dynamic loading is significantly different from that of normal concrete. TNO and the Delft University of Technology (DUT) started a research project aiming to design a special type of cementitious material that fractures into small fragments under impact loading, to be used in protective structures reducing the threat from debris throw. In the first part of the project the porous concrete was developed and investigated both experimentally and numerically. The first sections of this paper summarize the developments and findings.

The project second phase addressed the possibilities to upscale the production process from lab to semi-lab scale to enable ballistic tests and study the potentials of the new porous concrete for protection. Plates of 0.5x0.5x0.1m were produced successfully and exploratory ballistic tests up to 900 m/s were performed on the porous concrete, reference concrete slabs and also on "polymer filled porous concrete". The tests and results are described and analysed in the second part of the paper.

DEVELOPMENT AND ANALYSES OF POROUS CONCRETE

Material composition and properties

The porous concrete mixtures were produced in this study using aggregates at either one (2-4 mm or 4-8 mm) or two (2-4 mm and 4-8 mm, each 50 % by mass) standard size ranges. Cement paste content was highly decreased compared to that of normal concrete mixtures. Two different types of aggregates (crushed basalt and river gravel) and two binders (cement and silica fume) were involved in the production. Keeping the water to cement ratio constant at 0.30 for the strength requirements, the amounts and types of admixtures were adjusted according to the types of binders present in the mixtures. Two compaction techniques were used. Because the mixing and compacting procedures are lengthy, the use of a set retarder was essential in order to maintain the required level of workability of the cement paste. Cylindrical specimens that were 83 mm in diameter, 170 mm in height were cast, where two impact test samples were drilled from each specimen. In total nine different mixtures, denoted as concretes PRC1-9, were studied statically and dynamically. Background and details in composition, binders and compaction technique are reported in [Ozbek 2012, 2013]. The main results are given in Table 1, while the dynamic tests and diagnostic techniques are described in the next paragraphs.

Table 10. Compositional properties of the porous concrete mixtures

Mixture code	PRC1	PRC2	PRC3	PRC4	PRC5	PRC6	PRC7	PRC8	PRC9
Aggregate composition									
Crushed basalt (2-4 mm) (gr)	-	2000	1000	-	-	2000	1000	-	-
Crushed basalt (4-8 mm) (gr)	2000	-	1000	-	2000	-	1000	2000	-
River gravel (4-8 mm) (gr)	-	-	-	2000	-	-	-	-	2000
Porosity and strength data									
Porosity (vol%)	21.8	20.3	18.8	17.9	22.0	20.1	18.6	24.8	-
Compaction effort	high	high	high	high	high	high	high	low	low
Static compression strength (MPa)	34.8	41.9	50.5	29.6	31.6	44.8	48.8	15.9	13.1
Dynamic compression strength# (MPa)	66.5	76.8	86.0	56.2	53.1	79.7	84.4	26.3	21.8

in drop weight tests at velocity of 4.5 m/s.

According to the results obtained, the aggregate properties and compactive effort are the main factors that affect the dynamic performance of porous concrete. When mixtures containing different shapes and types of aggregates are compared, it is seen that increased texture and angularity contribute to porous concrete strength due to enhanced mechanical interlock, increased total surface area available for the adherence of cement paste and increased number of contact points. When two sizes of aggregates were used instead of using single sized aggregates, the dynamic strengths of porous concretes as well as their static strengths increased. For mixtures having single sized aggregates, as the size of the aggregates decreases, dynamic strength is also enhanced due to the increase in contact or bonding areas. Compaction is a factor that has a very important effect on the strength properties because it directly affects the porosity while intensive compaction enhances the strength properties. While aggregate properties drastically affect the strength properties, changing the cement paste composition did not have a very significant effect on the dynamic strengths of the samples.

Dynamic tests

Instrumented drop-weight impact tests were performed on different types of porous concretes to investigate their impact behavior. Laser Doppler Velocimetry (LDV) was selected as the monitoring technique to acquire the velocity history of the impactor surface at the interface between the impactor and the concrete target. In evaluating the results, impedance mismatch method was adopted where pressure versus particle velocity relationship is analyzed by intersecting the Hugoniot curves of the impactor and the target [Drumheller, 1998]. The situation of equal pressures and particle velocities at the interface is valid. In a special configuration where the sample is impacted between two materials of higher dynamic impedances, depending on the relative values of the impedances of the target and the two materials that are in contact with it, each reflection successively increases the amplitude of the compression wave propagating in the target as seen in Figure 1 [Kanel, 2004 and Kondo, 1981].

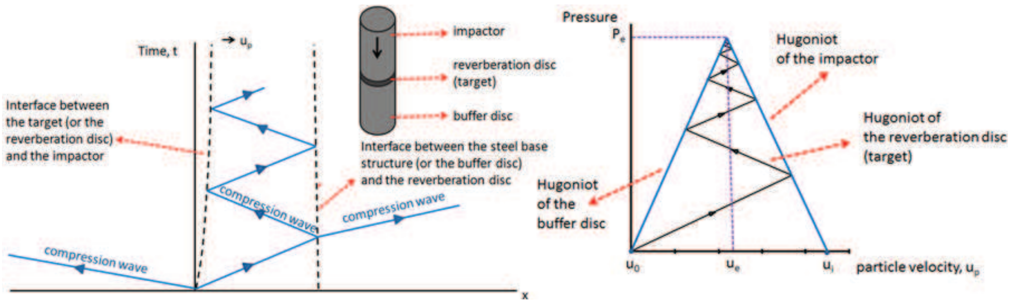

Figure 35 Impedance mismatch technique for linear elastic reverberation disc

In the pressure-particle velocity graph in Figure 1, the high strength linear elastic target material, that does not fail during the test, reaches a stress level of P_e and a particle velocity of u_e, which is for this case the maximum stress that can be applied by that impacting configuration (impactor and buffer disc) at that impact velocity. This analysis can also be applied when testing lower strength nonlinear materials such as porous concrete. Differently, in porous concrete tests, the reverberation situation continues until the stress within the concrete specimen reaches a level that generates substantial inelastic strains in the material where no additional load transfer can happen. In Figure 2, the spots indicated on the Hugoniot of the impactor are the points where the stress and particle velocities of the target and the impactor are equal which were also measured by the Doppler laser velocimeter during the drop weight tests.

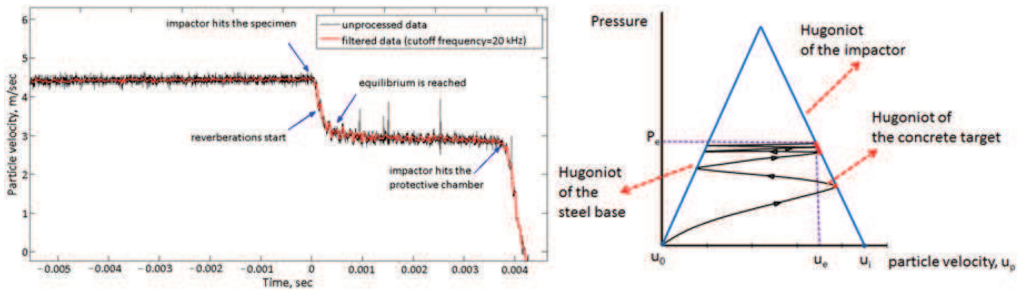

Figure 36 Particle velocity history - Impedance mismatch technique for reverberations in porous concrete

It should be noted that the particle velocity measured at the interface, on the impactor, reaches an approximately constant value when the pressure reaches equilibrium, as seen in Figure 2. This velocity value was named equilibrium velocity (u_e). The plateau that can be seen in the particle velocity history graph given in Figure 2 was very clearly observed in every porous concrete specimen tested, but at different values depending on the impacts strengths of the samples. The analyses of the particle velocity histories were done by first extracting the impact and equilibrium velocities from the particle velocity history graph as in Figure 2. For obtaining the stress from the measurements of the particle velocity, conservation of momentum law was used. In the conservation equation $P-P_0=\rho_0 C(u_i - u_e)$; P, P_0, ρ_0, C, u_i and u_e are the shock pressure, initial pressure, initial density, wave velocity, impact velocity and the equilibrium velocity, respectively. To examine the objectivity of the method, impactors with different dynamic impedances (aluminum and steel) have been applied. The same results for the target material properties were obtained. The objective test method has been applied to study nine different types of porous concrete. A moderate strength normal concrete was tested as well and comparedwith the literature and empirical equations.

Numerical investigations

For the numerical analyses, the finite element analysis software ABAQUS/Explicit was used where explicit direct integration is adopted. Concrete Damaged Plasticity Model was used to define the material properties of the cementitious phases that are present in the analyses. In order to represent realistically a porous concrete as a four-phase material (incorporating aggregates, interfacial transition zone (ITZ), bulk cement paste and air), the numerical study first started by acquiring the shapes and distribution of the aggregates in the samples through 3D computed tomography. A mesh generation program was developed to use this data in generating a finite element mesh. The numerical simulations were conducted using an axisymmetric geometry. Because contact properties are very important in the behavior of porous concrete, self-contact was defined between the concrete surfaces coming into contact while surface-to-surface contact was defined between steel and concrete.

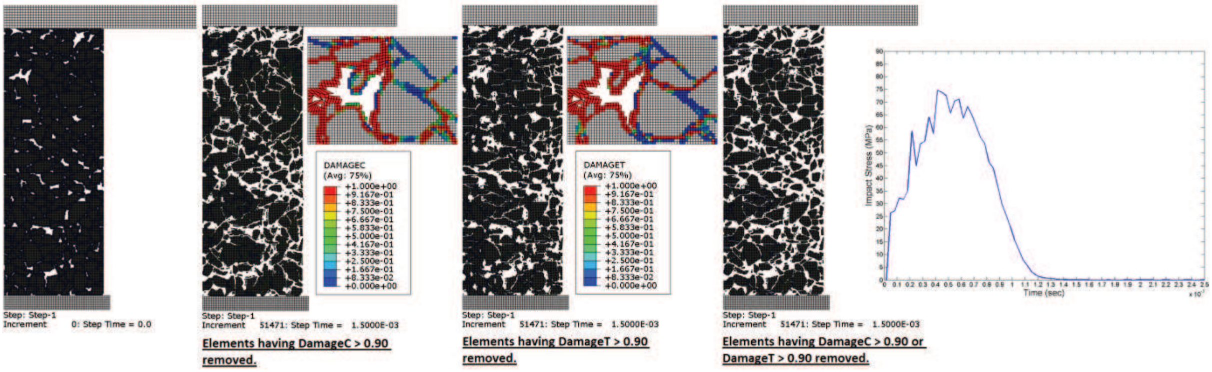

Figure 37 . Compressive and tensile damage variable contours (DamageC, DamageT > 0.90 removed) showing the crack propagation and the impact stress analysis results for a porous concrete mixture

In the analyses, the crack pattern formed under the impact loading was visualized through damage variable contours by removing the elements having compressive and tensile damage parameters higher than 0.90 from the mesh. This provides a good estimation of the fragmentation behavior which was verified by comparing with the high speed camera recordings. The numerical impact strength results obtained were also in a very good agreement with the experimental results. For the porous concrete shown, the impact strength was measured to be 76.8 MPa in the tests while the simulated strength was 75MPa.

Summary porous concrete development

The recipe to produce a porous concrete with a high porosity (about 20 vol %) and also static strength of normal concrete has been developed successfully. To analyse the dynamic properties and break-up at impact, a drop weight impact testing technique based on LDV was applied. Objectivity of the technique was verified. To enable the further development and parameter studies on the composition, a numerical model was developed. The simulation results were in good agreement with the experimental results both in terms of quantifying the impact strength as well as demonstrating a realistic crack pattern formation for the types of porous concretes that have been analyzed.

At this stage of the research it was decided to scale up the production process for the concrete type PRC1 and examine the ballistic performance. PRC1 was selected because of its strength and, moreover the drop weight tests confirmed that this mixture would have the highest potential for full fracturing under extreme dynamic loads.

BALLISTIC TESTS ON POROUS CONCRETE

Production at semi-lab scale

Testing the ballistic performance of the porous concrete requires larger test samples than can be produced under university laboratory conditions. To be sure that all effects (e.g. forces, cracking, fragmentation) can take place undisturbed within the sample without size effects, the slab size was set to 0.5x0.5x0.1m. These dimensions are based on numerical simulations for regular concrete. For the production method the requirement was that large scale production and processing of the mixture should be feasible in a realistic military environment. Additionally, the following principles were used:

- Materials (aggregates, cement, water and additives) were commercially procured. Physical, chemical and/or mechanical properties of the materials had to be (as much as possible) equivalent to the properties of the materials that were used in the design process of the mixture.
- For the mixing, compaction and finishing of the porous concrete known techniques and readily available machinery have been used.
- Simplification of all production processes had to be pursued, so use of unskilled labor in the future would be possible in a military setting.
- For handling of the panels during ballistic testing, the weight of the panels was dictated by the lifting capacity of two men.

As mentioned before it was decided to "reproduce the PRC1 concrete" for the ballistic tests. The aggregates in the PRC1 concrete consist of crushed basalt of 4-8 mm in size. Unfortunately these were commercially not available in large quantities, therefore the fraction of 5-8 mm was used. In total 18 panels of porous concrete were produced for ballistic testing. The panels were cast in layers of about 3 cm and compacted using a soil compactor. The size of the cast slabs were 1.25x0.60x0.1m. Test panels and specimens for reference material tests were sawn from these slabs. In addition the porous concrete, also regular concrete slabs were cast as a reference. The tests on the porous concrete provided a compressive strength after 14 days curing of 23.3 MPa (st.dev. 5.1 MPa) and a compressive strength after 28+ days curing of 28.5 MPa (st.dev. 2.6 MPa). For the reference concrete only a compressive strength equal to 35.4 MPa (st.dev. 2.8 MPa) after 10 days curing was determined.

The results of fully cured porous concrete gave a lower average strength (Δ of 4-6 MPa) than the original designed mixture. This difference is expected to be caused by the size change of the aggregate from 4-8mm to 5-8mm. Because of this change in size-range, the number of contact points (or total surface of bonding areas) decreases, resulting in a lower compressive strength of the porous concrete.

Ballistic experiments

The ballistic properties of the safety concrete compared to reference concrete as produced on larger scale have been tested at the ballistic lab of TNO. The experimental program consisted of tests with three different small calibre projectiles:

1. First series: Performing 4 tests, using **5.56 Ball SS109** at approximately 890, 900,930 and 960 m/s (One test per velocity).
2. Second series: Performing 8 tests, using **0.5 FSP 13mm** at approximately 300, 500, 700 and 900 m/s (Two tests per velocity).
3. Third series: Performing 8 tests, using **AP8 FFV** at approximately 300, 500, 700 and 900 m/s (Two tests per velocity).

The set-up consists of a frame positioning the concrete samples, witness plates made of Styrofoam, card board and aluminium with two high-speed camera's for visualisation of the fragmentation process during and after impact. The velocity of the projectile could be measured before and after penetration. The fragments of the concrete samples were caught in the witness plates and subsequently studied. Possible crack propagation at the front and back side of the samples has been monitored in-situ.

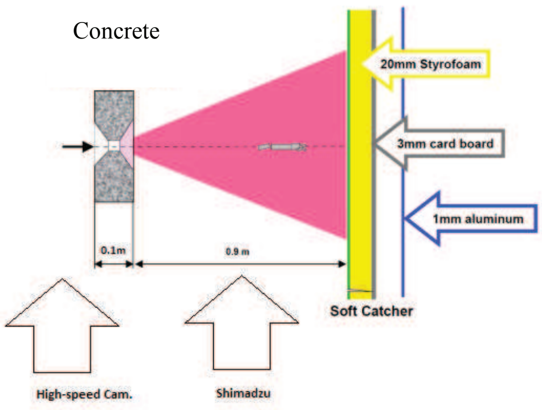

Figure 38 Test set-up ballistic experiments

Results and discussion of the Ballistic AP8 FFV experiments

In this short paper only the results for the AP8 experiments are presented and analysed. Also the complex interaction and penetration process cannot be discussed in detail, however the main items are addressed. Before this, the idea and motivation to study the ballistic performance of the porous concrete is provided.

Passive ballistic protection can be realised by (i) defeating the projectile (erosion, break-up), (ii) deflecting the projectile trajectory and/or (iii) absorbing the impact energy by the target material/structure. Because the porous concrete will fracture easily at impact, most projectiles will initially penetrate relatively easy. Penetration in this porous material is expected to occur in a volume of coarse, hard (basalt) aggregates constrained by the surrounding intact material. During the initial penetration phase, the passive confinement increases, while energy is absorbed by friction. During continued penetration while the aggregates are not crushed, the trajectory might deviate from the original impact direction. The passive confinement will strongly depend on the crater formation at the strike face. The main item of investigation in the performed tests and analysis has been whether the above specific features of the porous concrete could provide superior ballistic performance in spite of the lower density and reduced strength relative to standard concrete.

An engineering approach was used to quantify the target resistance to penetration. It uses the "resisting stress" (σ_{res}) defined as the average stress during the whole penetration/perforation process acting on the area equal to the original projectile cross section (¼ π D^2 for a cylindrical core with diameter D). Considering the energy balance of the projectile, the reduction in kinetic energy ($E_{kin,p}$) should equal the external work (ΔW) performed by the target and the deformation energy of the projectile ($E_{def,p}$). Assuming that the hard core AP-projectile will hardly deform, $E_{def,p}$ can be neglected and the energy balance for the projectile equals:

$$\Delta W = \tfrac{1}{2}.m_p.\left(v_{in}^2 - v_{out}^2\right) = \tfrac{1}{4}\sigma_{res}.\pi.D^2.DoP$$

with projectile mass m_p , the impact and residual velocities v_{in} and v_{out} respectively and the DoP the depth of penetration which equals the target thickness in case of perforation. The average resisting stress is used to compare the ballistic performance of the porous concrete to its reference, regular concrete. The data is assembled in Table 2. The perforation tests show a consistent result for σ_{res} (average value: 455 MPa). Unfortunately the data for the reference concrete is too limited to make a sufficient reliable comparison. Based on the single data point, the average resistance at perforation for the porous concrete is in the order of 2/3 of the regular concrete. For the "stop" experiments a similar average result is obtained from the raw data, i.e 691 MPa versus 1022 MPa for the reference concrete.

Table 11 Ballistic test data (7.62 FFV) and average resisting stress

Material	specimen	result	V_{in} [m/s]	V_{out} [m/s]	DoP [mm]	σ_{res} [MPa]
Porous concr.	SC8	Perf.	707	169	100	434
	SC7	Perf.	712	128	100	452
	SC7	Perf.	706	148	100	439
	SC7	Perf.	717	183	100	443
	SC7	Perf.	882	520	100	467
	SC7	Perf.	707	170	100	434
	SC3	Perf.	889	480	100	516
Porous concr.	SC2	stop	708	0	78	592
	SC2	stop	710	0	79	588
	SC6	stop	804	0	64	930
	SC6	stop	661	0	60	671
	SC6	stop	665	0	62	675
Reference concr.	RC4-1	perf	900	260	100	684
	RC1 3-2	stop	703	0	43	1059
	RC1 2-1	stop	724	0	49	985

The scatter in the results for the “stops” in the reference concrete is higher than for the perforation tests, which might be explained by the larger influence of the fully exploited- and therefore more dominant irregularities in the stop experiments. Furthermore in some of the experiments, the last part of the penetration channel deviated from the impact direction, so the simple 1D relation overestimates the penetration resistance. Further observations on the failure mechanism for the two materials has shown that the crater at the strike face were comparable, but for the porous concrete no cracks were observed outside the crater potentially beneficial for multiple impact. It was also observed from the video registrations of the impact events that spall debris for the porous concrete was minimal and consisted of “dust” plus aggregate(s). The spall of the reference concrete was also limited for the small caliber threat but showed larger pieces. Overall conclusion from this limited set of experiments is that the porous concrete does not provide better ballistic protection than regular concrete. To further investigate the influence of the porosity in the porous concrete on its ballistic resistance and separate this effect from potential other effects for this material, a small test series was performed with “polymer filled porous concrete”.

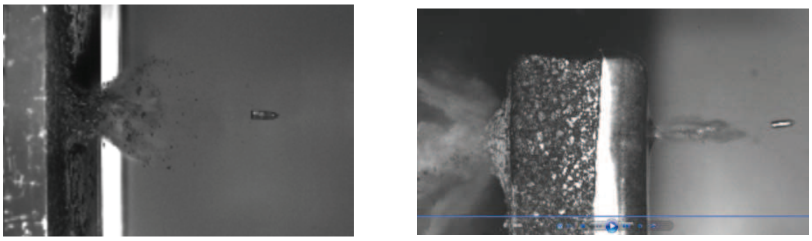

Figure 39 Ballistic tests. Left: porous concrete. Right: polymer filled porous concrete

Table 12 Ballistic test data (7.62 FFV) for polymer filled porous concrete

Material	result	V_{in} [m/s]	V_{out} [m/s]	DoP [mm]	σ_{res} [MPa]
Porous concr.	stop	896	0	85	870
Polymer filled	Perf.	955	132	100	824
	Perf.	982	219	100	844
	Perf.	985	372	100	767
	Perf.	983	386	100	754

The test results are provided in **Table** 3. Schematizing the penetration process in porous concrete, the undeformed projectile will compress the surrounding material. For a porosity of 0.25 the radius of the compressed zone will be about 2 x radius of the projectile, so very limited. Filling the pores with a polymer the influence the radius becomes “infinite” in theory (polymer and aggregate assumed to be incompressible). The radial confinement, and so the penetration resistance will increase considerably as a result. The test data confirms this enhanced resistance (although there's only one data point for stop). The polymer filled porous concrete performs even better than the reference concrete w.r.t. spall: the videos showed that spall did not occur for the filled porous concrete.

Comparison of the above tests on the filled porous concrete shows that the penetration resistance of the original porous material is mainly limited due to the open space in the concrete material, limiting the amount of high compression strength target material involved in the straining / fragmentation / friction process around the penetrating projectile. Filling the pores with low strength polymer, fully restores the original penetration resistance, even though the compressive strength of the polymer itself is small compared to that of the porous concrete. This effect is sufficiently interesting to motivate further investigation of this surprising effect.

CONCLUDING REMARKS

A porous concrete was designed and produced with a static compressive strength comparable to normal concrete (35 – 50 MPa). The rate effect on strength, for drop weight tests at 4 m/s, are also similar to normal concrete. The difference between the two materials is that the porous concrete fully fractures into aggregate sized particles. If this specific behaviour is beneficial for ballistic resistance was examined in an exploratory study using small calibre projectiles at velocities in the range of 700 - 1000m/s. The ballistic performance was evaluated and expressed using the average resisting stress, σ_{res} . The ratio of this stress for porous to regular concrete proved to be about 2/3. The spall at the rear face was smaller for the porous concrete. For the small calibre threat, the porous concrete did not perform better. When the pores were filled with polymer, the ballistic resistance increased significantly. The polymer filled porous concrete performed in the perforation tests even better than the regular, reference concrete while the formation of spall did not occur.

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