Fracture Mechanics of Concrete and Concrete Structures -
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The toughness of imperial roman concrete

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ABSTRACT: The concrete composites used to realize the monumental structures of Imperial Rome are remarkable engineering materials. While the endurance of intact constructions such as the Pantheon evinces the concretes' durability, such durability mostly serves to preserve the mechanical properties, which are responsible both for the monuments' original creation and continued survival. Despite their prominent role in the engineering achievements of the empire, these mechanical properties – particularly in tension and fracture – have not been comprehensively assessed. We first review the mechanical properties obtained through various experimental programs conducted on both authentic ancient composite core samples and their components, summarizing the major findings and outlining the remaining gaps in knowledge. We then qualitatively discuss the fracture of Roman concrete within the context of our own testing program, which will test both re-fabricated and authentic materials, with the aim of characterizing the fracture behavior that has contributed to the preservation of a significant component of engineering heritage.

1 INTRODUCTION

Between 60-160CE, Imperial Roman engineers honed their usage of concrete to create spanned monumental structures with designs that would violate present-day Civil Engineering building safety codes (ACI 318-08 2008). And yet a surprising number of these buildings are still extant today, some in excellent states of preservation and covered by their original unreinforced concrete vaults. Scholarly investigations tend to emphasize the architectural significance of the monuments instead of exploring the structural considerations invoked by the creation and survival of these daring constructions. Those rare studies that analyze structural behavior have been constrained by limited knowledge of the mechanical behaviors of the constituent concretes. Indeed, not a single analysis has incorporated the fracture mechanics of Roman concrete as a quasi-brittle material. Such analyses are critical for both preserving deteriorating structures and understanding the endurance of those still intact, as well as studying the ancient design conventions responsible for their conception and construction.

Fracture mechanics has not previously been applied to Roman concretes, mainly because little is known of their physical behavior as cementitious composites. The conglomeratic fabric contains fragmented brick and volcanic rock coarse aggregate of decimeter-scale dimensions bonded by a pozzolanic mortar, based on altered volcanic ash initially mixed with hydrated lime. The mortar has a relatively low compressive strength as compared with Portland cement mortars. The published mechanical testing data is sparse, and provides only scattered compressive strength values that are not accompanied by full load-displacement curves. Variability in mortar and coarse aggregate compositions further reduces the applicability of these results, particularly as they pertain to fracture of the concretes and the buildings realized therein. All told, describing the fracture behavior of these highly heterogeneous composites with widely varying constituents presents remarkable challenges. However, its characterization is vital to accurately assessing the safety of surviving structures, and understanding their extraordinary durability in response to a combination of differential settling on weakly consolidated bedrock and seismic ground motions over their nearly 2000-year life spans.

We begin with an exploration of published and unpublished mechanical test data for both the conglomeratic concretes and their assorted constituents. Examination of results for authentic historic specimens, modern laboratory-fabricated re-productions, and raw geologic materials provides initial insights into the potential application of modern concrete fracture mechanics to describe the fracture behavior of the ancient cementitious composites. From this review, we formulate several hypotheses about the fracture mechanisms of the concretes. We include a preliminary description of our proposed testing program, which will employ a novel experimental configuration to measure the fracture properties of laboratory-reproductions of an Imperial pozzolanic mortar, before culminating in the fracture testing of a significant volume of authentic ancient core samples from the Great Hall of the Markets of Trajan (c.110CE).

2 DESCRIPTION OF ROMAN CONCRETES

The meaningful discussion of Roman concretes is necessarily intertwined with the structures it realized. Accordingly, to provide context for a review of the mechanical properties of ancient concretes, we first examine the Great Hall in terms of its concretes to view Imperial Roman monumental concretes through the lens of an exemplary structure. The Great Hall is an appropriate choice because, through the generosity of those charged with its care, we have been able to meaningfully study the mechanical behavior and material composition of its structure in unprecedented depth (Jackson *et al*. 2009, Brune & Perucchio, in prep.).

When approaching the Great Hall, one sees mainly the brick facing that clads the concrete nucleus of standard Imperial Age wall construction (Fig. 1). The considerable dimensions of monumental buildings, combined with the tenacious bond between core and cladding, consign the facing to curing and weather protection functions while ensuring that the conglomeratic core acts as a structural skeleton. Although hidden from view, the concretes at the center of Imperial monuments were hardly afterthoughts. Indeed, these are remarkably complex materials, incorporating a diverse mixture of constituents from Rome's rich geologic surroundings to form a versatile and durable building material.

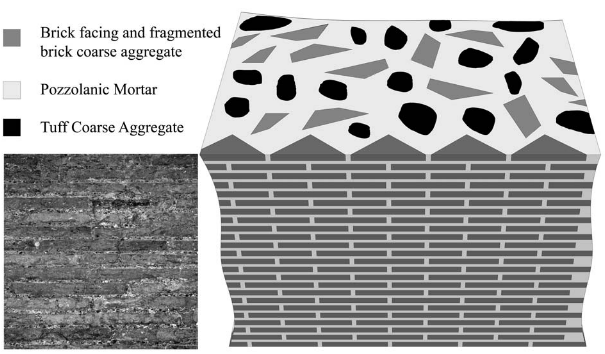

Figure 1. Photo of brick-faced concrete wall (bottom left) with schematic showing concrete nucleus. A typical facing brick is about 15cm wide.

The structural fabric of Roman concretes can be described on several length scales. On the structural scale, the material occupies large volumes – the Great Hall encompasses an excess of 3000m^3 of concrete – as a heterogeneous composite continuum. On the meso level, a pozzolanic mortar bonds decimeter-sized coarse aggregates (*caementa*). Various materials were used as *caementa*, with builders often vertically grading the aggregates by mass density to reduce the self-weight of upper sections of structures, especially in vaults.

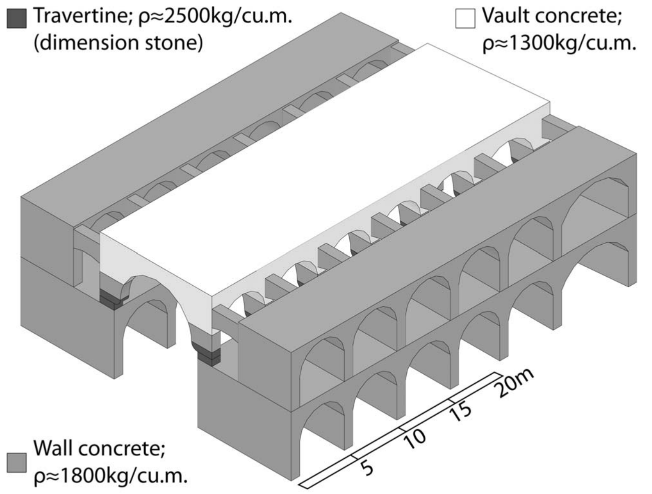

Figure 2. Computational solid model of the Great Hall, showing the three structural-scale materials.

The wall and vault concretes of the Great Hall (Fig. 2) feature at least two distinct aggregate mixtures (Jackson *et al.* 2009). The *caementa* of the wall concrete include fragmented bricks (~1600kg/cu.m) and two tuffs: the compact and relatively durable Tufo Lionato (~1700kg/cu.m) and the porous and weakly durable Tufo Giallo della Via Tiberina (~1500kg/cu.m). The lighter vault concrete contains almost exclusively Tufo Giallo della Via Tiberina. The wall mortar was produced by combining hydrated lime with Pozzolane Rosse altered volcanic ash aggregate, mainly in small gravel- to sand-sized scoriae, and very small quantities of ground, sand-sized Tufo Lionato aggregate. The binding matrix of the wall mortar contains alumina- and alkali-cement gels and strätlingite. In contrast, the vault mortar contains notable amounts (~33 volume%) of light grey pumice (~800kg/cu.m), a smaller quantity (~15% volume%) of heavier Pozzolane Rosse (~1700kg/cu.m), and a very small quantity (<5 volume%) of ground Tufo Lionato. The cements are as yet unknown. Taken together, the two concrete formulations evince Roman builders' sophisticated and intentional deployment of available materials towards the controlling of self-weights. But how did the diverse material combinations translate into mechanical properties?

3 PREVIOUS EXPERIMENTAL TESTING OF ROMAN CONCRETES & COMPONENTS

The numerous confections of Imperial Roman concrete are marked by widely divergent aggregate constituents. Due to the general unavailability of authentic specimens and the challenge of laboratory refabrication, no comprehensive experimental testing of these various materials has been executed to robustly characterize their overall mechanical behavior. The experimental programs to date have focused largely on compressive strength. These findings confirm the expected variation in performance among the different formulations, which encourages an examination of the mechanics of the constituent aggregate components.

3.1 *Testing of ancient roman concretes*

For samples cored from Ancient structures, Lamprecht (1984) published the first modern mechanical test results in the form of compressive strengths, with a single measurement of the elastic modulus (18GPa). Cores were obtained from a variety of sites, structures (from a roughly 250-year range), and locations within the structures. Lava, tuff (type unspecified), basalt, sandstone, quartz, and slate are all mentioned as coarse aggregate. Diverse compositions of mortar were also observed, with different types of limestone – either dolomitic or pure – identified as the quicklime source and pozzolana (provenance, color, alteration facies, and maximum grain size were not noted) only identified for certain samples. No information about the relative percentages of coarse aggregate and mortar was provided. Limited information about the dimensions of the prismatic test samples was included, usually in the form of an edge length (mean=6.7cm), except for two cylindrical samples of 15cm diameter. The wide variability in composition and provenance of the samples is evident in the considerable scatter of the measured compressive strengths, with a mean of 12.9MPa (stdev=5.5MPa) over 52 samples.

Samuelli Ferretti (1996) oversaw mechanical testing of Ancient Roman concrete cores obtained from the Port of Trajan at Fiumicino and Hadrian's Villa in Tivoli. The Fiumicino cores were taken from the foundations of a warehouse and measured 15cm in diameter and between 25.5 and 28cm in height, with alternating strata of brick and tuff (unspecified) coarse aggregate. The relative proportions of brick, tuff, and mortar were measured by area from maps of the exterior core surfaces as (35, 20, 45), (2.5, 35, 62.5), and (19, 16, 65). The samples from Hadrian's Villa consisted of two prismatic blocks of $10x10x14cm^3$ and one that was $11x11x22cm^3$. Both blocks were taken from the collapsed vaulting of the *Sala a Tre Esedre* and contained only brick aggregate; relative proportions were not recorded. Uniaxial compression tests recorded both the compressive strength (mean=3.60MPa, stdev=1.96MPa) and elastic modulus (mean=2.9GPa, stdev=1.8GPa) of the samples. Several complete stress-strain curves were also obtained. Also, significantly, modulus of rupture tests measured the bending tensile strength for two Hadrian's Villa samples (0.68, 0.78 MPa). However, no additional information concerning specimen size or complete load-displacement curves was provided for the bending tests.

In addition, samples from the Basilica of Maxentius included cores from a large section of the collapsed main vault, two of the barrel vault base walls, and the foundation. Specific information about the cores is limited to their geometry and bulk density. The aggregate constituents were not recorded. All samples were cylinders with 15cm diameters and heights between 30 and 38cm, except for three prismatic blocks of $35x35cm^2$ cross section and 45cm height. The samples were extracted along an axis perpendicular to the stratification of the aggregate layers. The volumetric proportion of mortar in the concrete was said to fall between 40-60%, with the additional remark that the lowest proportions of mortar appear in the zones of the structure where the building process was executed "most carefully." Uniaxial tests measured the compressive strength of nine samples (mean=4.6MPa, stdev=1.4MPa) and the elastic modulus of three (mean=2.7GPa, stdev= 0.9GPa). No complete load-displacement curves were reported (Giavarini et al. 2006).

As a whole, previous mechanical testing of ancient concrete cores provides scattered compressive strengths over statistically insignificant and highly varying populations. Specimen sizes were generally only two or three times larger than the *caementa*, the largest heterogeneity, further restricting the applicability of the strength results to structural-scale behavior. Furthermore, aggregate constituents were seldom catalogued with sufficient rigor. Altogether, it seems that the composite nature of the ancient material and the source of its vulnerability in structures – mainly tensile fracture – were not sufficiently well understood to inform the experimental programs' goals. Only two small samples were used to measure tensile strength, and no measurement of fracture properties has been published.

3.2 *Component testing*

The variability evident in the composite responses asserts the importance of the component mechanical behaviors to achieving a more robust estimation of the overall composite response. Several testing programs have made valuable contributions by measuring the mechanical properties of mortar and coarse aggregate constituents of the ancient concretes.

3.2.1 *Ancient roman bricks*
Samuelli Ferretti (1996) tested ancient bricks, commonly used in fragmented form as *caementa*. Bricks of widely varying provenance and quality, generally taken from wall facings, were sawed to create 29 sample sets. From these, prismatic specimens measuring 15x15x30mm^3 were subjected to compression (mean=17MPa, stdev=5.9MPa) and direct tension tests (mean=3.33MPa, stdev=1.25MPa). The elastic modulus (mean=13.4GPa, stdev=4.7GPa) was also measured along with a ductility ratio, defined to be the quotient of the strain at ultimate failure (after softening) and the strain corresponding to the peak stress. This ratio averaged 2.26 (stdev=0.35); a few complete stress-strain curves are described as "characteristic of a fragile material".

3.2.2 *Ancient roman mortars*
Samuelli Ferretti (1996) created pozzolanic mortar samples using hydrated lime and sieved Pozzolane Rosse combined in Vitruvian proportions (1:3, by volume). Only ash particles smaller than 2mm were used; in contrast, the mortars in the Great Hall include Pozzolane Rosse scoriae up to 1.5cm. The amount of Roman tap-water used was specified according to a volumetric ratio with lime of (1.39:1); it was not stated how much water was used to initially hydrate the lime, making a water to cement ratio unavailable. Prismatic beams of 40x40x160mm^3 were cast, de-molded after an unspecified amount of time, and cured in a lime-water solution. After curing at 7, 28, 90, 180, and 360 days, modulus of rupture tests were followed by compression tests on the broken halves. The results indicate a marked reduction in flexural (30%) and compressive strength (10%) between the 90-day and 180/360-day samples. This suggests a complex hardening process, perhaps due to chemical phase transitions in the pozzolanic cements during curing. For the 360-day samples, a mean flexural strength of 0.95MPa (stdev=0.10MPa) and mean compressive strength of 12.07MPa (stdev=1.02MPa) were measured. The mean elastic modulus, measured during compression tests, was 3GPa (stdev=0.1GPa).

3.2.3 *Roman volcanic tuffs*
Various tuffs from the Roman region were frequently used as *caementa* in monumental constructions. While heavier leucititic lavas and travertine were used in foundations and lighter pumice and *scoriae* were sometimes used in vaults, volcanic tuffs (and brick fragments) comprise the majority of coarse aggregates in Imperial conglomeratic wall concretes. Numerous tests by De Casa *et al.* (1999, 2007) and Jackson *et al.* (2005) on two commonly used tuffs – Tufo Giallo della Via Tiberina and Tufo Lionato (those found in the Great Hall concretes) – indicate quite scattered material characteristics and rock strengths.

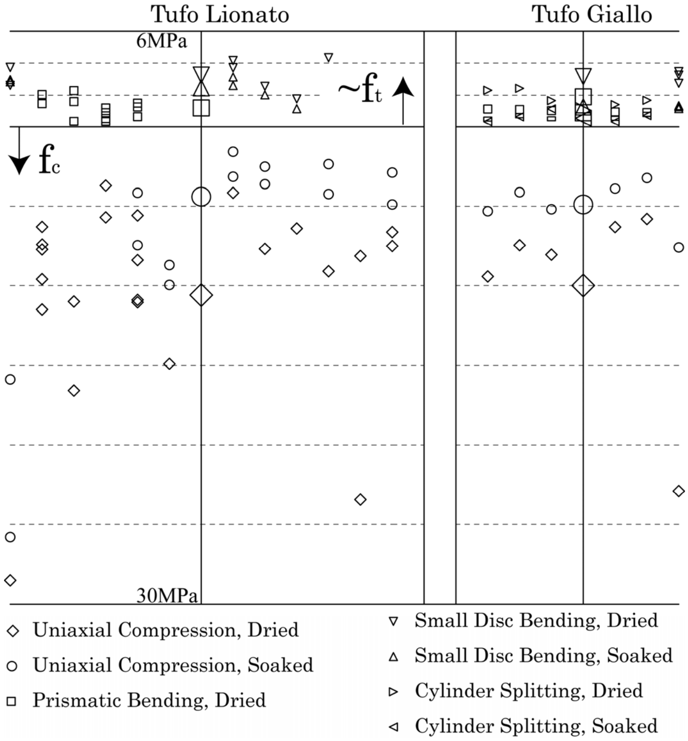

Figure 3. Strength data for Tufo Lionato and Tufo Giallo della Via Tiberina. Each column corresponds to a different quarry. Large markers represent the mean for each type of test result. After De Casa *et al.* (1999, 2007) and Jackson *et al.* (2005).

The variation in results (Fig. 3), likely in part due to dissimilar experimental setups, occurs not just between quarries but also for different locations and stratigraphic levels in a single quarry. The scattered strengths of the two tuffs reflect their heterogeneous, pyroclastic fabrics, which are composed of variable proportions of vitric, lithic, and crystal fragments bound by zeolite (and calcite) cements. Furthermore, weathering of pumice glass in some tuff specimens produces clay mineral that weakens the cohesion of the tuff, thereby reducing mechanical strength and durability (Jackson *et al.* 2005).

Tuff coarse aggregates can form 50 volume% of the concrete fabric of monumental walls and vaults. Therefore the characterization and inclusion of the mechanical behaviors of the Roman tuff lithologies is central to an accurate composite material model describing the fracture of Imperial concretes. The widespread variability tuff mechanical properties, along with their dependence upon petrographic-scale characteristics, highlights the importance of using data appropriate to either a specific tuff provenance or a well-documented petrographic analogue.

3.3 *Synopsis of Experimental Results*

The accumulated experimental data identifies several obstacles to understanding the mechanical behavior of Roman concretes. First, there is the familiar difficulty with concrete constructions in traversing from the structural scale (~m) to the experimental scale (~cm). For Roman concretes, this difficulty is compounded by the fact that, given typical coarse aggregate dimensions, a sufficiently representative experimental scale is on the order of decimeters or even meters. The strongly heterogeneous fabric of the concretes further complicates the analysis of fracture behavior. Furthermore, the scattered mechanical and unknown fracture behaviors of the coarse aggregates, combined with the length-scale on which they appear in the concretes, presents a major source of variability. Finally, the mortar is a composite material in and of itself. The particle size distribution of the Pozzolane Rosse aggregate ranges from coarse silt- to medium gravel-sized in the pozzolanic mortars of the Great Hall and other monuments (Jackson *et al*., 2007). These fragments have been shown to redirect crack propagation in the cementitious binding matrix (Fig. 4).

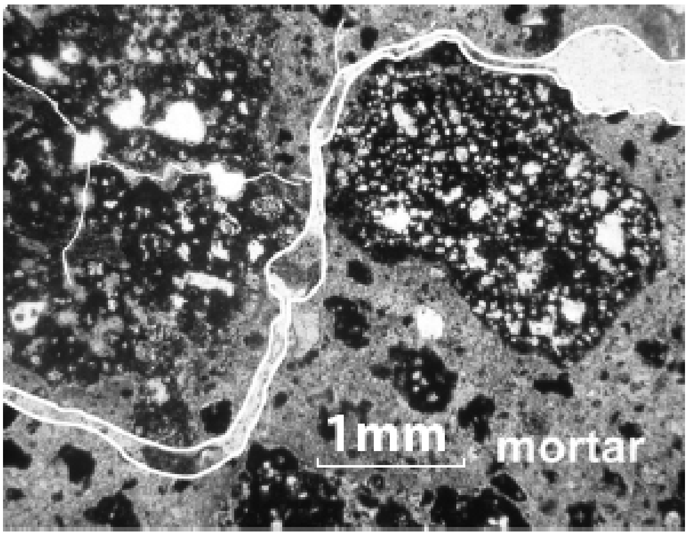

Figure 4. Photomicrograph of the curving trajectory of a debonding crack that follows the perimeters of Pozzolane Rosse scoriae in a mortar sample from the Great Hall, produced by a point source load test (after Jackson *et al*. 2009).

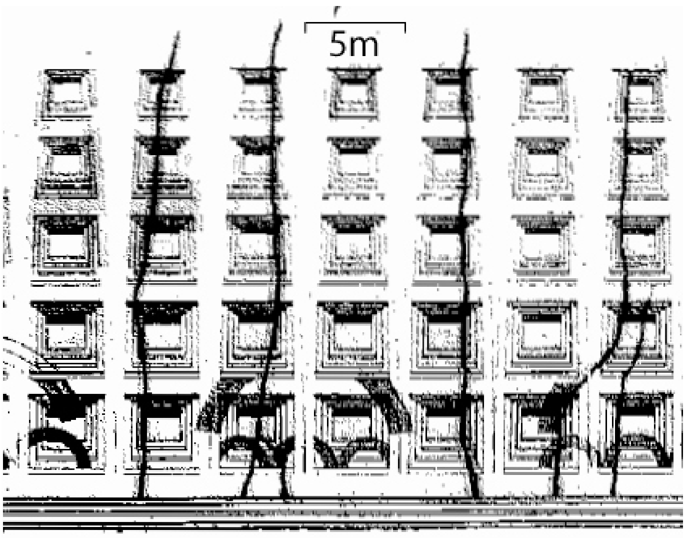

Figure 5. Survey of macrofractures afflicting Pantheon's dome at the time of a restoration (after Terenzio 1934).

Additionally, the impossibility of obtaining sufficiently large and isolated mortar specimens from ancient concretes requires all tests to occur on reproductions fabricated in the laboratory. Even when informed by the best (but inevitably limited) understanding of Roman materials and practices, recreated mortar samples lose a vital degree of accuracy from differences in curing and aging. Furthermore, a third element in the Roman concrete composite, the interfacial transition zones (ITZs) between mortar and coarse aggregate *and* within the pozzolanic mortar, seems to substantially influence the initiation and propagation of microcracks. While it is not yet known how the ITZs surrounding *caementa*, possibly at the same decimeter length-scale, affect fracture propagation, the millimetric zones around scoriaceous mortar aggregate have been observed to impact fracture trajectories (Jackson *et al*. 2009).

4 THE FRACTURE OF IMPERIAL ROMAN CONCRETE

The mechanical behavior, particularly in fracture, of Roman concretes is central to understanding how the daring monumental structures were initially conceived, according to the empirical processes widely thought to govern Imperial Roman design, and how they have endured for nearly two millennia in an active seismic zone on relatively poorly consolidated bedrock (Molin *et al*. 1995, Rovelli *et al.* 1995).

Our experimental program aims to characterize the mechanical behavior on length scales that are appropriate for the constituent materials and extrapolate as accurately as possible this description to the structural scale, on which the formation of structural-scale macrofractures that imperil surviving monuments occurs (Fig. 5). Accordingly, our program will measure fracture properties of the diverse constituents of Roman concrete and use the results to characterize an appropriate fracture model for the composite. For example, the fracture energy of the composite, G_{f_comp}, *could* be found to depend on the fracture energies and tensile strengths of the mortar and coarse aggregates, and the tensile strengths of the interfaces:

$$G_{f\_comp} = \xi_1 \cdot G_f^{mortar} + \chi_1 \cdot f_t^{mortar} + ... + \chi_n \cdot f_t^{ITZbrick} \quad (1)$$

where ξ_i = the i^{th} fracture energy influence coefficient; and χ_i = i^{th} tensile strength influence coefficient. The model for the fracture properties of the composite, parametrized as in equation 1 in terms of the component properties, may be further informed by fractographic observations that identify additional physical parameters describing the fracture of the composite material. The model will then be optimized (*i.e.*, the values for χ_i, ξ_i, determined) based on both experimental results and numerical modeling of the fracture processes of the cores of ancient conglomeratic concrete. Indeed, the program will focus on testing numerous 20cm-diameter drill cores of the wall concrete of the Markets of Trajan, which cores have been generously entrusted to our research program by the Sovraintendenza Archeologica di Beni Culturali di Roma. As described above, the pozzolanic mortar and *caementa* are similar to many Imperial constructions. Ideally, the parametrized fracture model derived from the Great Hall wall concretes could then be particularized to describe the behavior of other Imperial concretes.

The careful evaluation of the fracture energies of components of the composite concrete is a first step towards the derivation of such a model. Such measurements would supplement test data already obtained from the concretes of the Great Hall. Jackson *et al*. (2009) used point source tests on discs 3.5cm in diameter and 1.5cm thick to approximate tensile strengths of the components of the wall concrete. The preparation of test specimens isolated specific elements of the composite concrete fabric, so that the point-load tensile strengths were measured for *caementa* (brick, Tufo Lionato, Tufo Giallo della Via Tiberina), the pozzolanic mortar, and each of the respective *caementa* interfaces (Fig. 6).

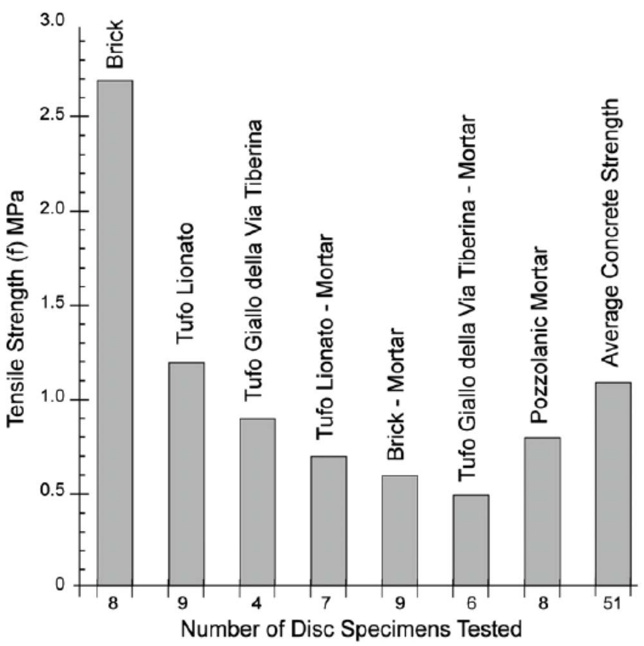

Figure 6. Tensile strengths of components from the wall concrete of the Great Hall, as measured by point source tests.

The point source strengths supplement, in an approximate sense, the extremely limited data on the tensile strength of Imperial concretes and make important suggestions of elements in the composite concrete fabric in which fractures may nucleate. The small sample size and complicated stress fields, however, limit the applicability of point-source results to understanding fracture on the structural scale. At this scale, the formation of fracture process zones (FPZs) surrounding nucleating and propagating fractures could, conceivably, substantially reduce a monument's overall stability by weakening load paths in highly stressed regions or, equivalently, reducing the local tensile strengths of load-carrying regions.

In modern concretes, the FPZ grows as distributed microcracks converge on increasingly larger length scales ranging from voids in the cementitious matrix (10e-6m) to the average aggregate particle (10e-3m), depending on the local morphology and stress field (van Mier 1997). As the crack driving energy increases, the bridging microcracks in the process zone eventually reach a length scale larger than that of the aggregate particles, and a macrofracture may form/advance.

The larger range of component length scales (up to 10e-1m) in Roman concretes makes the development of the FPZ difficult to intuit qualitatively. In stead, we introduce Hillerborg's non-dimensional brittleness number to explore the process zone quantitatively:

$$\beta = (D \cdot f_t^2) / (E \cdot G_F) \tag{2}$$

where D = any structural dimension; f_t = tensile strength; E = elastic modulus; and G_F = fracture energy. Modern dam concretes may present a rough analog to Roman concretes. Their coarse aggregate sizes approach those of typical Roman *caementa*, while experimental measure of their composite fracture behavior records demonstrably larger fracture energies compared to typically-graded modern concretes (Deng *et al.* 2008). This agrees with a general trend of increasing fracture energy with maximum aggregate size (Elices & Rocco 2008). In modern concretes, one can envision the propagating fracture requiring increased energy to produce a more tortuous path around and/or a tougher path through the larger aggregate particles, but still following the same general trajectory, with variations occurring on a smaller (~mm) scale. This is not necessarily the case for Roman concretes, where the larger aggregate constituents could significantly alter fracture propagation paths and characteristics.

A simple two-dimensional schematic (Fig. 7) illustrates several possibilities. The composite fracture energy for cases (A-C) can be expressed as follows:

$$G_F^{(A)} = (G_{Ic\_1} \cdot L) / L \tag{3}$$

$$G_F^{(B)} = (G_1 \cdot L_1 + G_{ITZ1|2} \cdot L_{1|2}) / L \tag{4}$$

$$G_F^{(C)} = (G_1 \cdot L_1 + G_2 \cdot L_2 + G_{ITZ1|3} \cdot L_{1|3} + G_4 \cdot L_4) / L \tag{5}$$

where $G_{Ic\_1} = G_{F\_1} = G_1$ = the fracture energy of the mortar; $L_{1|2}$ = the length of the crack path along the interface between the mortar and a Tufo Giallo della Via Tiberina *caementa* fragment (Fig. 8); $G_{ITZ1|3}$ the fracture energy of the interface between brick and mortar; and so on. In the absence of any measured data, extremely rough approximations for the respective fracture energies could compute a "composite" fracture energy that increases by around 50% in case B, and almost doubles in case C, illustrating the potential of the large aggregates and interfaces to alter composite fracture properties. The estimates assume a homogeneous mortar and do not take into account centimeter-scale scoria and lava aggregate, which can impact fracture propagation (Figs. 4, 7d&e).

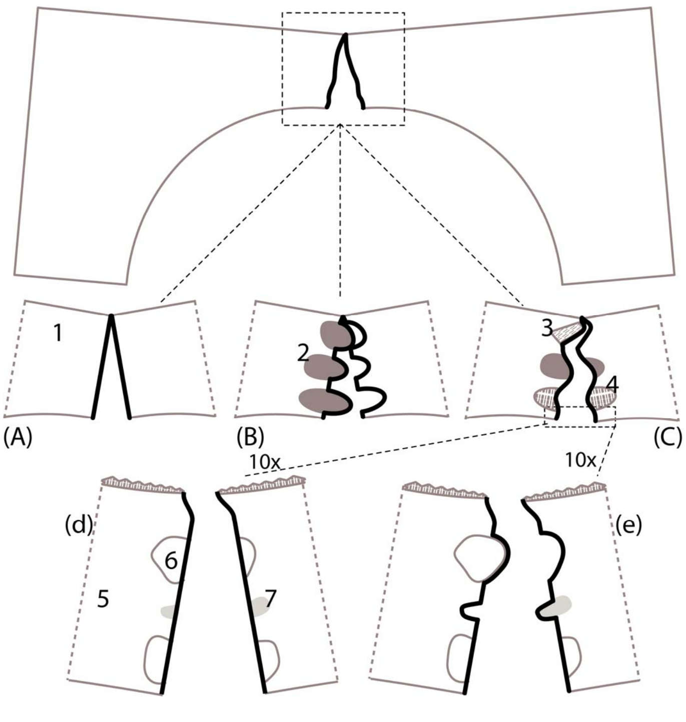

Figure 7. Schematic showing possible meso-scale (A-C) and micro-scale (d-e) mechanisms of fracture in a Roman concrete vault.

It seems reasonable to postulate relatively large fracture energies for Roman concretes. Combining this with their lower tensile strengths (Fig. 6), equation 2 suggests large, possibly meter-scale, process zones preceding structural-scale macrofractures in Roman concretes. How such a process zone might influence the propagation of fracture and consequent structural-scale destabilization of a monument is a complex question. However, in view of the extraordinary survival of many Imperial age monuments, exposed to two millennia of differential ground subsidence and seismic ground motions, we tentatively suggest here that the mechanical strength of the concretes, likely modest but certainly sufficient, is of secondary importance. Perhaps far more relevant to the structures' continued stability are the fracture energies of their concretes, empirically evident in the ability of the monuments to absorb changes in external and internal energies over many centuries.

While much study is needed to explore this phenomenal endurance, our initial hypothesis posits the dissipation of energy into the development of widely distributed but relatively weakly coalesced or bridged process zones. These zones of dispersed, small-scale (with respect to the meso-structure) cracking effectively delay the localization necessary for the nucleation, linkage, and propagation of fractures on structurally perilous scales. This hypothesis introduces further questions: at what point does the accumulation of these potentially isolated microstructural damage zones imperil the building on a structural scale? And how suddenly? What role do the unusual and highly durable alumina- and alkali-rich pozzolanic cements of the Roman mortars play in the resistance of the concrete fracture? And, more globally, could conglomeratic composite concretes, perhaps characterized by the ability to absorb energy via widely distributed, weakly coalesced process zones, have applications for sustainable concrete construction in seismically active areas?

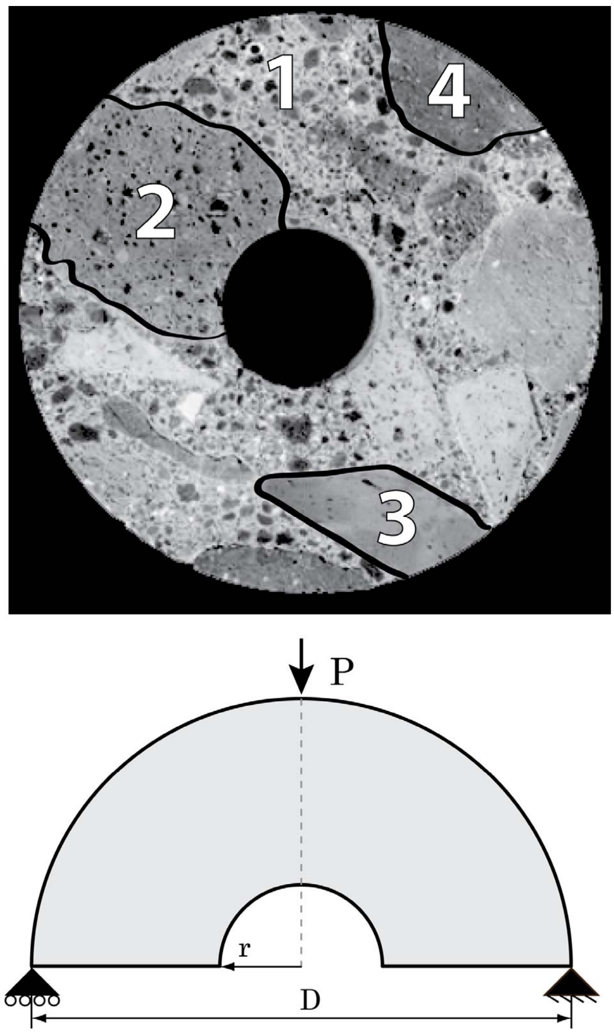

Figure 8. Top: photograph of wall concrete core with components outlined: 1-pozzolanic mortar; 2-Tufo Giallo della Via Tiberina; 3-brick fragment; 4-Tufo Lionato. The outer core diameter is 20cm. Bottom: schematic of test design. D = 20cm; r = 5cm.

We begin exploring these questions with the fracture testing of laboratory re-productions of Imperial Roman mortar. The geometry of the Great Hall drill cores – eccentric, hollow, thin-walled cylinders – motivates a novel test design that loads arc-shaped specimens in three-point bending (Fig. 8). The objectives are to observe the microstructures of the mortar reproductions before testing, to record the microstructural nucleation, coalescence, and propagation of fractures on specific length scales during testing, and to produce estimates for the fracture energy and tensile strength of the re-fabricated mortars based on measurements recorded on the experimental scale. Specimens will be tested after 7, 28, 90, 180 days, and at multi-year curing periods to observe how the strength and fracture properties develop as cementitious phases advance. Details concerning sample fabrication, testing, and data reduction, will be published along with experimental results and analysis as the project proceeds.

5 SOME PRELIMINARY CONCLUSIONS

The fracture testing of the mortar reproductions will contribute the first measurement of the fracture energy of Imperial Roman concrete, which is likely a fundamental component in the formulation of a fracture description for the composite material. Past mechanical characterizations of Roman concretes have focused on compressive strength. Test results show considerable scatter, which attests to the highly heterogeneous nature of the composite material and the importance of understanding the length scales on which particular mechanical and fracture properties should be measured. Still, the reported strengths, however dispersed, in conjunction with the structural analysis of Imperial monuments generally indicate that the concretes have strength sufficient for the static loads of the extant architectural designs (*c.f.*, Brune & Perucchio in prep.).

Mechanical analyses to determine the factors behind the survival of these designs – and the cementitious materials that preserved them while subjected to centuries of seismic and subsidence events – requires investigation into how microcracks in the composite concrete nucleate, propagate, and potentially resist fracture at the structural scale. The wide variation of aggregate compositions and consequent mechanical properties of the conglomeratic composites and their components makes the identification of structural-scale material properties by direct experimental testing extremely difficult. Instead, our approach will be to measure relevant fracture and mechanical properties on the micro- and meso- scales. These data will inform a parametrized model for the composite that will aim to create a reasonably bounded envelope for the structural-scale fracture behavior, incorporating variations in component properties and their relative importance in the composite response.

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REFERENCES

A.C.I. 318 Building Code Requirements for Structural Concrete and Commentary. Farmington Hills, MI: ACI.

Brune, P. & Perucchio, R. in prep. Roman Concrete Vaulting in the Great Hall of Trajan's Markets. Journal of Structural Engineering.

De Casa, G. & Lombardi, G. 2007. Caratteri Fisico-Meccanici del Tufo Giallo della Via Tiberina (Roma). Rendiconti Lincei 18(1): 5-25.

De Casa, G. et al. 1999. Il Tufo Lionato Dei Monumenti Romani. Geologica romana 35: 1-25.

Deng, Z. et al. 2008. Comparison between Mechanical Properties of Dam and Sieved Concretes. Journal of Materials in Civil Engineering.

Elices, M. & Rocco, C. 2008. Effect of aggregate size on the fracture and mechanical properties of a simple concrete. Engineering Fracture Mechanics 75: 3839-3851.

Giavarini, C. et al. 2006. Mechanical Characteristics of Roman 'Opus Caementicium.' In S. Kourkoulis (ed.), Fracture and Failure of Natural Building Stones. Dordrecht: Springer.

Jackson, M.D. et al. 2005. The Judicious Selection and Preservation of Tuff and Travertine Building Stone in Ancient Rome. Archaeometry 47(3): 485-510.

Jackson, M.D. et al. 2009. Assessment of material characteristics of ancient concretes, Grande Aula, Markets of Trajan, Rome. Journal of Archaeological Science 36: 2481-2492.

Lamprecht, H.O. 1984. Opus caementicium: Bautechnik der Römer. Düsseldorf: Beton-Verlag.

Molin, D. et al. 1995. Sismicità di Roma. In Memorie Descrittive della Carta Geologica d'Italia: La Geologia di Roma I, edited by R. Funiciello, 331-407. Rome: Istituto Poligrafico e Zecca dello Stato.

Rovelli, A. et al. 1995. Previsione del moto del suolo e modellazione degli effetti locali. In Memorie Descrittive della Carta Geologica d'Italia: La Geologia di Roma I, edited by R. Funiciello,416-432. Rome: Istituto Poligrafico e Zecca dello Stato.

Samuelli Ferretti, A. 1996. Rapporto sulle prove di laboratorio ed in situ effettuate sui componenti, in Materiali da costruzione e tecnologie costruttive del patrimonio archeologico e monumentale romano con particolare riferimento al tipo laziale ed all'opus latericium. Roma.

Terenzio, A. 1934. La restoration du Pantheon de Rome. Conservation des monuments d'art & d'historie: 280-285.

Van Mier, J.G. 1997. Fracture Processes of Concrete: Assessment of Material Parameters for Fracture Models. Boca Raton, FL: CRC Press.