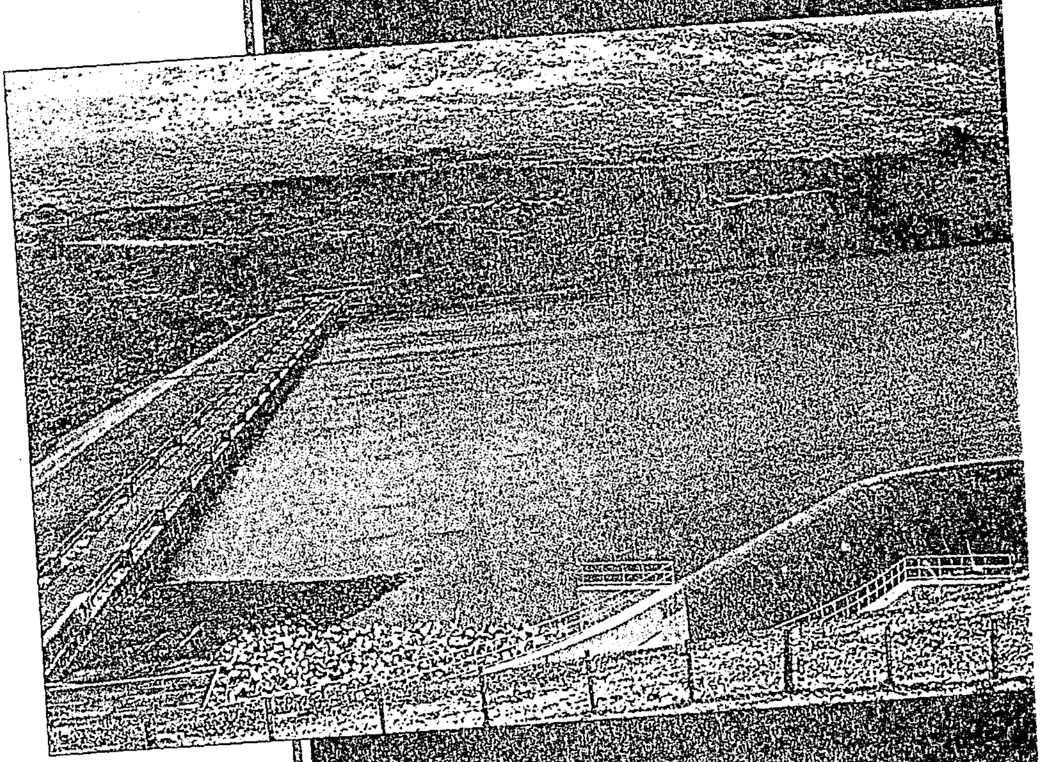
Concrete In The Service Of Mankind

Appropriate Concrete Technology



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RAVINDRA K. DHIR
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There is no alternative to concrete as a volume construction material for infrastructure. This raises important questions about how concrete should be optimised for short and long-term cost effectiveness, whilst allowing flexibility for radical innovations and developments.

Appropriate Concrete Technology forms the Proceedings of the three day International Conference held during the Congress, Concrete in the Service of Mankind, 24-28 June 1996, organised by the Concrete Technology Unit, University of Dundee. It brings together developments in concrete technology for various applications and new approaches to specification for material and structure performance. Topics discussed include criteria for appropriateness, implications of harmonisation, versatility of concrete, binder technology, non-ferrous reinforcement and design and construction.

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AN INNOVATIVE LABOUR-INTENSIVE METHOD FOR CONSTRUCTION OF ARCH BRIDGES USING UNCUT STONE AND MORTAR

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ABSTRACT. Lack of adequate infrastructure in rural South African communities, coupled with the abundance of uneducated and unemployed people, has prompted authorities to encourage labour-intensive construction methods. One such technique, using natural uncut stone and cement mortar, is described. Inadequate knowledge of the material strength and magnitude of stresses experienced in these structures has prompted investigation aimed at formulating guidelines for the design and construction of more efficient structures of known reliability. A procedure has been developed for testing the compressive strength of large stone and mortar cubes. Some of the failure characteristics indicate that incorporation of minor changes to current practice may well yield a material with superior properties. Measured live-load-induced stresses are used to validate a theoretical finite element model, to evaluate alternative arch shapes, providing greater spans and reducing the volume of material required.

Keywords: Labour-intensive, Uncut stone masonry, Cement mortar, Arch bridge, Cube strength, Finite element analysis.

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INTRODUCTION

Many impoverished communities throughout Southern Africa experience periods of isolation when floods wash away parts of their road infrastructure, or just make road use impossible during the rainy seasons[1].

In 1992, the former Lebowa Government's Roads and Bridges Department called for tenders for the installation of bridges as part of its road management system. The engineers were prompted, because of a materials supply problem, to explore alternative construction methods. A technique, similar to that used in Zimbabwe[2,3] to build stone-arch causeways, was proposed and successfully implemented. In addition to overcoming the immediate problem of a materials shortage, the new construction method also provided several social benefits:

a) This construction method is highly labour-intensive, providing jobs for hundreds of local people who would otherwise be destitute.
b) Most of the money spent on each bridge, is invested into the local community through wages, hiring of local subcontractors and local purchasing of material.
c) This building technique minimises energy input by using abundant local material and is therefore likely to be sustainable, thus empowering developing communities to provide their own transportation infrastructure.
d) The design philosophy of a rigid mass structure, aims to achieve very low stress levels, thereby increasing the tolerance of the structure to geometrical and material variations, so as to accommodate the relatively low level of local skills.

Many of these principles have subsequently been recognised, encouraged and implemented by the South African Government in its Reconstruction and Development Program[4] and the National Public Works Program[5].

DESCRIPTION OF CONSTRUCTION METHOD

Once the foundations are in place, sheets of corrugated iron are pre-cranked to the shape of the intrados and positioned over the foundations to provide temporary support to the arch span. In the case of large spans, these sheets are propped with gum poles to help bear the weight of the masonry until it becomes self-supporting (Fig 1). In some areas alternative centering using 50mm saplings, covered by old cement packets, and supported by temporary mud brick walls has been successfully deployed[1].

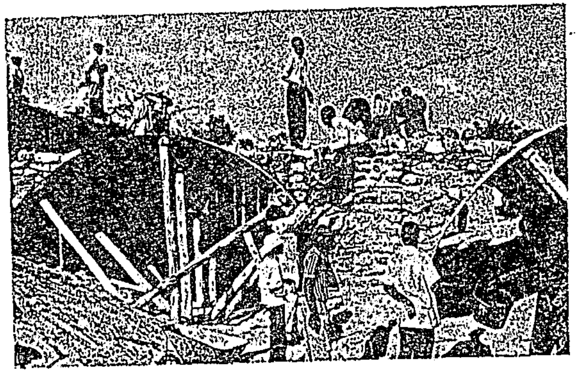

Figure 1 Construction of a typical bridge showing the temporary corrugated iron and gum pole centering used to form a 2,7m radius arch.

Workers gather stones (typically weighing anywhere from 10 - 40kg), from the fields nearby. Sand from the river bed nearby is used to make a cement mortar. The cement:sand ratio (by volume) varies from 1:4 to 1:3. The manual assembly begins by embedding individual stones into a thick layer of mortar. The stones are not cut or dressed in any way, and are placed dry in intimate contact with one another. This procedure is followed; horizontal layer upon horizontal layer, until a solid structure results. As a precaution, a grid of high tensile reinforcing steel has been placed horizontally in both directions, immediately above the crown of the arch in the initial structures. This steel is placed in a thick bed of cement mortar, of a 1:3 cement:sand mix. Another bed of mortar (or preferably concrete) is used to even out the bridge deck to form a trafficable surface.

STRENGTH OF STONE-MORTAR MATERIAL

Cube Tests

As traditional 100mm and 150mm concrete testing cubes are too small to accommodate even the smaller stones used in this material, an alternative test was developed by Rankine[6]. For ease of fabrication, the traditional cube shape was maintained, but the overall dimensions were increased to accommodate the large stones. *Initially cubes of* 300mm, 400mm and 500mm were chosen as a means of exploring different possible sizes. The 300mm size proved too small to accommodate all but the very smallest stones and the 400mm size only permitted one, or at most two, of the larger stones. Thus, it was decided that the 500mm size, shown in Fig 2, was the most representative of the material and has subsequently been adopted for further testing.

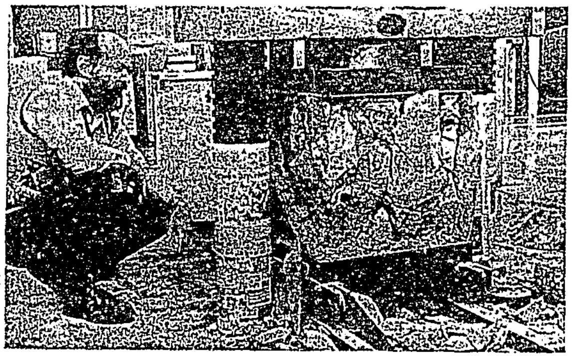

Figure 2 Large scale compression test on a 500mm *stone-mortar cube weighing* 300kg.

Cube stresses

Rankine et al[7] describe some large cube tests which were carried out as a preliminary indicator of the strength of the materials used for these bridges. The cubes were made on site, using weathered hand gathered stones and the same procedures as were used for the bridges themselves. A subsequent series of tests[8] using *quarried dolomite rock (graded in various* combinations using individual stones weighing between 1 - 40kg), and the same strength mortar has produced a stronger material. The 28 day compressive strength of these cubes is presented in Table 1. The weathered stones with a friable chalky surface do not appear to provide as good a substrate for the bonding of cement mortar, as do quarried rocks with fresh faces.

Table 1 Results of compressive tests.

Cube size (mm)	Mass (Kg)	Failure load (KN)	Failure stress (MPa)
300	60	1260	14,0
400	149	1435	9,0
500	-	2406	9,6
*500	-	3138	12,6
*500	-	3293	13,2

The first three specimens contained hand gathered stones with weathered faces. Specimens prefixed with an asterisk represent an average of three test cubes containing quarried dolomite (with fresh clean surfaces). The 28 day 100mm cube mortar strength for all specimens was between 14 and 15 MPa.

Consequences of orientation of stones

To simulate the *compressive* thrust generated above the crown of the arch, load was applied to the cube *specimens* perpendicular to the plane of casting. (As flat elongated stones are currently positioned horizontally, axial compressive stresses over the crown of the arch, tends to be applied *parallel* to the stones' longitudinal axes). Where failure of the specimens appeared to be initiated by *bond failure* at the stone-mortar interface, this often resulted in a wedging or *cleaving action* by the long slender stones which lay parallel to the axis of applied load. It is *interesting* to note that similar observations have been recorded in a parallel investigation[8] of physical model melanges during a study of rock mechanics.

Large flat stone surfaces, when placed horizontally, were observed to exacerbate the problem of early bond failure. The horizontal surfaces tended to trap bleed water on its upward migration and form a *void* between the mortar and the stone. Hence, it is proposed that further testing establish quantitatively the effect on compressive strength of placing elongated stones *radially rather than horizontally.*

STRESSES WITHIN THE ARCH

Measurements in-situ

To gain an initial understanding of the *magnitude* and nature of the stresses and strains within the arch structure, *measuring devices* were made by fixing electronic strain gauges onto concrete prisms as shown *in Fig 3.* These were then built into arches during construction. At a stage when the bridge became trafficable, a truck with an axle load of 100 kN, was driven across the bridge (see Fig 4), to record the stresses in each device at various axle positions. The first series of stress measurements confirmed that the live-load-induced strains, and hence stresses were very low. The measured tensile and compressive stresses, induced by this live-load did not exceed 0,074 MPa. It was evident that very sensitive instrumentation was needed to provide more reliable data. Subsequently, a mechanical strain multiplying device has been developed[9] in an effort to amplify the the strain before it is recorded. This results in a more sensitive signal, without any sacrifice in clarity and without generating more noise. The data gathered will be used for validation of further theoretical models.

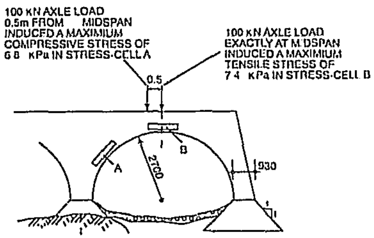

Figure 3 Recorded induced stresses in a 2,7m radius arch with corresponding axle positions

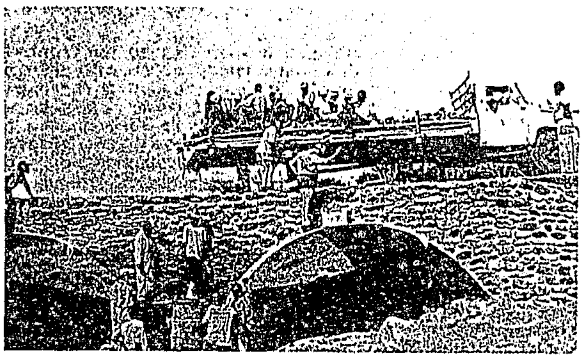

Figure 4 Live-load-induced strain test

Finite element analysis

Because of the inherent difficulties in measuring self-weight-induced stresses, it has so far only been possible to predict these values theoretically. A preliminary finite element model has predicted self-weight-induced stresses of up to 0,6 MPa, in the structure illustrated in Fig 1. Only once this model has been fully validated by confirmation of predicted live-load-induced stresses with measured live-load-induced stresses, can this value be safely relied upon. Thereafter, it is envisaged that the finite element model may be confidently used as a powerful exploratory tool for modelling new structures to be built from this material.

COMPARISON OF STRENGTH AND STRESSES

The low measured and predicted stresses within these structures, compared with the measured strength of the material, provides some temptation for speculation that an adequate margin of safety against compression failure exists. Preliminary indications suggest that allowable stresses should be limited to below one MPa, since traditionally, masonry arches have been assigned very high factors of safety against crushing of between 10 and 40[10]. It is also prudent to remember that the greatest contributor of stress in these structures appears to be the theoretically predicted self-weight-induced stress (which presently remains to be validated).

CONCLUSION

This labour-intensive method of bridge construction has fulfilled a dual function of providing infrastructure and creating job employment for hundreds of destitute people. A comprehensive set of design and construction guidelines are considered a prerequisite to structural engineers widely adopting this initiative. Preliminary research indicates that minor changes to current practice may result in a material with superior properties. Blasted quarried rocks, as opposed to weathered rocks, appear to produce a stronger material. Further research is proposed to quantify the effect of orientation of stones with respect to the structures' stress trajectories and the use of finite element models as exploratory tools for predicting stresses in proposed structures is recommended.

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MANPOWER MOTIVATION IMPROVES QUALITY IN CONSTRUCTION

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ABSTRACT. Construction is a labour intensive process and manpower in one of the productive resources in it. Quality is directly related to the performance which is a function of motivational level of workers. Legitimate motivation to the manpower results in the improvement of quality in construction products. The study is based on the data collected from 24 different construction projects sponsored by the government. The data are analysed considering factors affecting morale and motivation of workers and their effect on quality of construction. The results of the survey report are presented in this paper. On the basis of data collected, the authors conclude that construction management, legitimate facilities including job satisfaction, proper training, and presence of some motivational plans etc., result in higher level of performance of workers which ultimately results in improvement of quality in construction. The authors also suggest suitable methods regarding motivation and co-ordination of manpower to achieve higher levels of quality in construction.

Keywords : Manpower, motivation techniques, construction, quality improvements

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RUBBLE MASONRY ENGINEERING: AN APPROPRIATE DESIGN PHILOSOPHY TO ENSURE SUCCESS

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SYNOPSIS

The creation of employment opportunities for the destitute has become a priority in developing countries in recent years. Rubble masonry, a building material consisting of natural uncut stones manually embedded in a cement mortar matrix, has aroused great interest amongst engineers intent on increasing the labour content of their projects.

Technical research and a case study of several bridges and dams, which have been constructed in Zimbabwe and South Africa indicate that a labour based design philosophy is prerequisite to ensure success. To be sustainable, rubble masonry structures need to be as cost efficient as conventionally designed structures. To date, successful projects have been cost competitive through more efficient utilisation of physical resources rather than by exploitation of labour. This is largely due to the fact that cement is the only constituent purchased. It is highly unlikely that a conventionally conceived design could be adapted to be a successful labour intensive project, albeit extremely modified. Traditional design codes are blind to the limitations of human resources and there is no established source of technical data with which to calculate rational designs for more ambitious projects using this material. Research at the University of the Witwatersrand has concentrated upon developing designs and specifications to promote and sustain this initiative.

1.0 INTRODUCTION

1.1 The global need for self-sufficient solutions

The world's population is forecast to increase by about a billion persons in the next decade. Ninety percent of this increase will occur in the low-income developing countries, in which resources are already severely strained[1,2]. Such rapid growth will surely underscore the problems already facing these countries; unemployment, starvation, disease, homelessness, lack of infrastructure and illiteracy.

Foreign "aid" and transfer of modern first world infrastructure has not alleviated these problems in the past and is not likely to do so in future[3]. Such initiatives rapidly deplete the recipient country's most critical resource, *its funds for capital development*, and drown it in unsustainable debt[4]. There is growing recognition of the need for more appropriate technological solutions that make efficient use of abundant local resources such as unemployed people and natural raw materials to promote sustainable development[5,6].

Many initiatives to create employment for the destitute, by implementing conventionally designed construction projects at the same time as increasing the labour content, have made a negative economic contribution[7]. Although they may be shown to have benefited isolated communities, these projects frequently incur a cost premium to execute manually[8]. This is damaging to a developing country's economy and therefore ultimately unsustainable[9]. To be sustainable, labour intensive technology has to compete with existing technology. In many cases this may prove impossible without refinement through continuous research-based development and training[10].

1.2 The proven history of rubble masonry

History suggests that labour intensive rubble masonry construction has consistently proven exceptional in its ability to provide sound infrastructure and employment opportunities for developing nations. Its origins as a building material for dams and bridges date back to Roman times. Hundreds of these structures have stood the test of time in an exemplary manner and many are still in service today, having survived many centuries and a few more than two thousand years[11]. During the latter half of the 19th century and the beginning of the 20th century, engineers such as Rankine (1865) and Krantz[12] began to explore the material properties of rubble masonry and apply rational design philosophies to its structural use. However, the onslaught of the industrial revolution in the western world reduced the cost of cement and facilitated a more efficient method of construction using crushed aggregates and mechanical batching plants capable of higher levels of output at reduced cost. Consequently, significant further developments in the knowledge and use of rubble masonry as a structural material ceased. Only a few developing countries including Pakistan and India appear to have continued to use rubble masonry since that time.

In Zimbabwe, a resurgence in the use of rubble masonry followed the unilateral declaration of independence by the Rhodesian government in 1965 to reduce dependency on foreign currency, particularly for the consumption of liquid fuel and the replacement of machinery. Engineers Wild and Robertson[13], Mainwaring and Hasluck[14] and Wootton and Stephens[15] are to be commended for their contributions towards efficiently utilising rubble masonry as a practical cost effective structural material.

2.0 THE COMPETITIVE ADVANTAGE OF RUBBLE MASONRY

The Zimbabwe experience had profound influence over the adoption of rubble masonry construction in South Africa following policies[16,17] to increase employment opportunities. Several rubble masonry structures have been successfully built at considerably lower cost than conventional alternative designs[13,18,19], despite the high remuneration demanded by the South African labour-force. This competitive advantage over more conventional alternatives would appear to emanate from the simultaneous occurrence of most of the following factors:

- The only material purchased is cement.
- Provided the stone and sand are sourced within close proximity of the site, their acquisition costs may be limited to the wage remuneration of gatherers and possibly blasting costs if rock has to be quarried.
- Materials' transportation costs are minimised because cement (which typically accounts for only 7% of the weight of a rubble masonry structure) is the only material hauled any considerable distance.
- Unlike concrete, rubble masonry requires no vertical support during curing, therefore dispensing with the need for much costly formwork.
- The conservative design approach adopted for most rubble masonry structures results in components with low aspect ratios. This can be of considerable advantage if the working face is large enough to serve as a safe platform for the labourers, thereby obviating the need for much scaffolding.
- No crushed aggregate is used. Therefore, there are no costs of crushing, washing and screening plants.
- Because the rock is sourced locally, completed rubble masonry structures automatically blend into their surrounding landscapes and are positively perceived to be environmentally acceptable.

In contrast, the Balfour Dam[20,21] (also recently built with similar materials in South Africa), was never conceived as a labour based project, but was adapted, subsequent to the original design, to accommodate more labour. This contributed to an increased total cost of R1,036 million over the estimated cost of conventional construction; a cost premium of 20%. It consumed vast quantities of imported crushed aggregate. The boulders collected for plums were not found in abundance close to the site but frequently had to be loosened from the alluvium far upstream by mechanical backactors before they were manhandled vast distances over poor terrain onto a few large stockpiles for collection. Permanent formwork made from precast concrete blocks was used and this was anchored into the structure with substantial steel reinforcement.

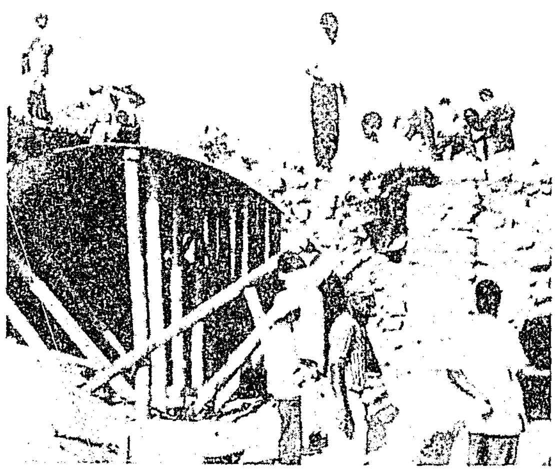

Fig 1 One of many low level labour intensive rubble masonry bridges successfully built in the Northern Province of South Africa in direct competition with conventional designs.

3.0 MATERIALS

3.1 Stone Selection

The American Civil Engineer's Handbook (revised 1941), provides brief statistics of 144 unreinforced masonry dams built throughout the world before that time[22]. It reports numerous failures which account for thousands of lost lives, yet, no mention is made of any failure arising as a direct result of geological material deficiency. Some of the geological materials successfully employed worldwide include: Granites, Gneiss, Trap, Syenite, Limestone, Sandstone, Quartzite, Nummultic conglomerate, Shale, Mica schist, Serpentine, Porphyryte, Linneite slate and Crystalline limestone marble. More specifically, in South Africa: Dolerite, Quartz vein, Weathered granite[23] and Foyaite[18] have been used in the recent past.

King[21] describes a simple test deployed at the Balfour Dam site to control the quality of stone. Stones are dropped from a height of 1,2m onto a concrete slab. Those which survive intact are acceptable. After a few demonstrations, labourers quickly learn to visually identify unsuitable materials from a distance.

Where loose boulders occur in abundance near to the construction site, manual collection and stockpiling have obvious cost saving and employment creating advantages. As natural boulders become more scarce, blasting from nearby quarries becomes more economically viable, although perhaps not always environmentally acceptable. One advantage in specifying quarried rock is that all the exposed faces are fresh and sound, whereas gathered rock often exhibits a friable weathered skin. In a preliminary series of compressive tests on rubble masonry cube specimens containing dolerite inclusions with friable weathered surfaces, Rankine et al[23] observed that loss of adhesion at the interface, caused by detachment of the weathered skin, appeared to govern total failure. In a subsequent series of tests[24] containing dolomitic inclusions with sound, clean fresh blasted faces, this phenomenon was not observed and failure was accompanied by fracturing of both rock and mortar.

3.1.1 Size of boulder considerations

The primary incentive to incorporate large boulders in rubble masonry structures is economic (conserving costly cement). By selecting a variety of stone sizes and carefully packing progressively smaller stones into the irregular interstices between the larger stones, the mortar content can be reduced. There are practical limitations governing the minimum size of filler particles which can be manually inserted into these interstices, and consequently further mortar reductions can only be achieved by increasing the size of the largest boulders. The Americans frequently used boulders, called "derrick stones" because they had to be lifted by derricks, which were as large as 50 cubic feet ($1.4m^3$) weighing up to 4 metric tons. This practice is reported to result in a 50% mortar saving requiring only 24% mortar by volume[22]. The British are reported to have used stones up to 10 metric tons[25]. In India[25], Zimbabwe and South Africa, stones of a size which a man can handle have been used, resulting in a mortar content of approximately 45% by volume. Croswell[27] has proposed a mass of 32 kg to border on the upper threshold of what a labourer can reasonably be expected to lift and manoeuvre repeatedly without assistance. Larger boulders which are too heavy to be manhandled can be fragmented into manageable chunks by manually striking them with a sledgehammer. This was clearly demonstrated during the construction of the Maritsane Dam where tough granite boulders were manually broken with surprising ease[13]. It is interesting to note that in India, any mortar used in excess of 45% was considered waste and charged to the contractor[25].

Walker et al [28] and the United States Bureau of Reclamation[29] used large scale cylinder tests (up to 48 inches long by 24 inches in diameter {1220X600mm}), in an effort to explore the effect of maximum size of aggregate (up to six inches {150mm}), upon the compressive strength of concrete used in dams, such as Hoover Dam. This confirmed a size effect relationship that for a given cement:water ratio, strength is inversely proportional to aggregate size.

Similarly, Rankine has developed a procedure [27] to explore the size effects of embedding large rocks in the weaker mortar matrix of rubble masonry (see Fig 2). A series of 15 compressive strength tests, on large 500mm cube specimens, was conducted to determine the relationships between inclusion size, compressive strength and variability of properties[24]. The results are presented in Table 1. The first three specimens were cast with pure mortar (without any inclusions) in an attempt to isolate the cubic specimen size scale effect. Clean blasted dolomite was used. It is interesting to note that contrary to the established concrete aggregate size effect law, specimens containing bigger inclusions showed a clear trend towards yielding higher compressive strengths, although unfortunately, at the expense of increased strength variability. The reasons for this phenomenon are complex and possibly the result of several simultaneous mechanisms such as the larger flat stone faces exerting greater bilateral constraint to the dilating mortar, the reduction of interfacial area and the corresponding reduction of probable crack initiation sites.

Fig 2 Unconfined axial compression testing of a 500mm rubble masonry test cube weighing over 300kg.

Cube	No.	Stress at Failure MPa	% Volume Rock
Mortar only	1	9.240	Nil
	2	9.164	Nil
	3	9.340	Nil
$\bar{x}$		9.248	
σ		0.088	
$\sigma/\bar{x}$		0.95%	
1-4 kg rock	4	10.024	41.4
	5	10.088	42.0
	6	10.228	42.4
$\bar{x}$		10.113	41.9
σ		0.104	0.5
$\sigma/\bar{x}$		1.03%	1.2%
7-15 kg rock	7	13.940	41.4
	8	12.808	45.2
	9	12.768	39.6
$\bar{x}$		13.172	42.0
σ		0.665	2.9
$\sigma/\bar{x}$		5.05%	6.8%
25-40 kg rock	13	14.088	39.7
	14	14.404	40.6
	15	12.600	46.4
$\bar{x}$		13.697	42.2
σ		0.963	3.6
$\sigma/\bar{x}$		7.03%	8.6%
25-40 kg &1-4 kg	4	11.328	56.4
	5	15.680	57.3
	6	10.648	49.8
$\bar{x}$		12.552	54.5
σ		2.730	4.1
$\sigma/\bar{x}$		21.75%	7.5%

100mm mortar cube strengths
1 15.07 mPa
2 14.84 MPa
3 14.74 MPa
$\bar{x} \Rightarrow$ 14.79 MPa
$\sigma \Rightarrow$ 0,3 MPa
$\sigma/\bar{x} \Rightarrow$ 2,0%

$\bar{x}$ = mean

σ = standard deviation from the mean

$\bar{x}/\sigma$ = coefficient of variation from the mean

Table 1 The strengths and strength variations of 500mm rubble masonry cubic specimens containing various sizes of rock inclusions.

3.2 Mortar quality

Analysis of rubble masonry structural failures[11,22] show weakness of the mortar matrix, although often the result of its long-term deterioration, to be the most likely culprit of the very small proportion of material induced failures. Before the development of modern Portland cement in 1811, mortars incorporated lime and later hydraulic lime as binding agents[30]. In India, the lime was mixed with clay, which presumably acted as a natural pozzolan, for the construction of tall masonry dams[31]. In Zimbabwe, straight slag and fly ash extended cement mortars are used for economy.

Rankine[24] has identified bleed-water to be a potential threat to the interfacial bond between mortar and rock. This problem appears to be most pronounced when sharp coarse river sands (as are common in Southern Africa) are used. Bleed-water is then trapped below the large horizontal faces of rocks as it attempts to migrate upwards as shown in Fig 2. Consequently, any precautions that can be taken to reduce bleeding are recommended. de Beer[13] addressed the problem by utilising fine pit sand as a filler in the Maritsane Dam and Shaw[18] employed a proprietary blended masonry cement containing an air entraining agent for the mortar mix design used in the Bakubung Dam.

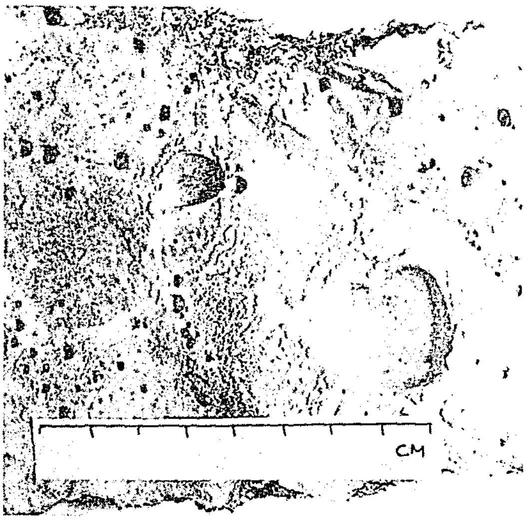

Fig 3 The entrapment of bleed-water below horizontal surfaces of flat stones causes a reduction in bond at the interface. The portion of mortar shown in the photograph became detached at a very low stress.

Rankine[30] has questioned the use of mortars containing air entraining agents for future rubble masonry structures where the bond characteristics offered by the aggregate surfaces might be less favourable than the exceptional foyaite of volcanic origin used by Shaw. This follows reports that the air entraining admixtures, commonly found in blended masonry cements, reduce the bond strength by bubbles interrupting the intimate contact at the interface as well as blocking the entry of paste into minute fissures.

3.3 Mortar batching and mixing

It is possible to make consistent high quality mortar by hand mixing but in rubble masonry construction practice this is unlikely to be achieved for the following reasons:

1) The concept of strength being proportional to the cement:water ratio is difficult to convey to an uneducated man; especially as it is in direct conflict with his interests; since his remuneration is proportional to his output which can most easily be increased by adding more water.

2) Hand mixing of large quantities of mortar is very vigorous exercise and not sustainable for long periods without large rest intervals. Consequently, problems of non-homogeneous mortar and bottle-necking of the entire operation by shortage of mortar supply can realistically be anticipated.

Mechanical gravity action mixers are relatively cheap ite of plant, they are very efficient and they produce consistent homogeneous mortar. If the mixer is operated by a technician with a stopwatch, its output can be subtly manipulated to increase the tempo of the entire rubble masonry operation, thereby driving the masons, transporters and batching crew to greater levels of output. This hypothesis appears to be supported upon examination of production statistics from recent rubble masonry projects in South Africa. Production rates of 0.2-0.3m^3 of placed rubble masonry per labourer per day have been reported[31,32] in cases where mixing has been done by hand whereas rates of 0.8m^3[13,18] have been reported where mechanical mixing has been employed. However, if this trick is exploited excessively, it may result in an excessive use of mortar.

3.4 Curing

Without proper attention to curing, the potential strength of the mortar and hence the rubble masonry will never be reached and consequently money spent on cement will have been wasted. Subsequent layers of rubble masonry may prevent the underlying material from drying out and are frequently considered to be an acceptable alternative to traditional curing[23]. However, over weekends and holidays considerable evaporation of moisture can take place if appropriate precautions are not taken to combat this loss. Wrapping and frequent watering are probably the most practical methods of curing rubble masonry and engineers who seriously desire proper curing should appreciate that any provisions which reduce the difficulty getting water to the exposed faces will greatly improve the chances of their wishes being fulfilled. With little planning effort the energy requirement to transport water for curing can be eliminated if water is siphoned through hose pipes from a higher altitude.

4.0 JOINTS

Construction joints, which occur at interruptions in casting rubble masonry, are often responsible for initial seepage in dam structures and are a potential sources of shearing planes. Wegmann [12] has proposed that horizontal courses be avoided and that the rubble be laid so that stones break joints in all directions. There is wisdom in this philosophy, provided that these courses are inclined towards the principle stress axes so that they are approximately normal to the stress trajectories. Merriman[22] has recommended that large stones be left projecting above the general level at the end of a day's work to interlock with subsequent work, thereby preventing the formation of shearing planes which might otherwise arise between two smooth flat surfaces. Where there is a suspicion of inadequate curing of previous work, the mortar surface should be cut back to remove any laitance and porous mortar so as to expose sound mortar and provide a good key. Bond with previous work may be improved by wetting the underlying masonry with a little water, but not so much as to prevent all suction, and coating it with a cement slurry.

5.0 CONCLUSION

Rubble masonry construction has a well-proven reputation for providing developing countries with employment opportunities and sound basic infrastructure at minimal cost. Despite the primitive state of this art, it is nevertheless capable of competing directly with sophisticated modern alternatives provided it is sensibly deployed to accommodate the intricate requirements of a low-skilled labour-force. However, the employment creation potential of rubble masonry will not be realised so long as engineers are deprived of the necessary knowledge to confidently build more ambitious structures of known reliability. This knowledge cannot be generated without the increased support of research and development initiatives.

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R G D Rankine, Y Ballim and
R T McCutcheon

Strength, variability and failure mechanisms of rubble masonry concrete under compression

Synopsis

Criteria that govern the failure mechanisms, variability and strength of rubble masonry concrete (RMC) are explored with reference to the behaviour of analogous particulate composites. Contiguous particle interaction and the potential for anisotropy are noted as two distinguishing characteristics that may account for much of this material's unique behaviour. Failure appeared to be initiated by debonding of the stone-mortar interface parallel to the principal stress long before the specimens attained their maximum stress. Variability of mechanical properties was found to be a function of anisotropy and heterogeneity. Although the interfacial surface area (between phases) in RMC is at least 10 times smaller than in conventional 19 mm stone concrete, it is demonstrated that this is not accompanied by a corresponding increase in the interfacial bond stress. However, it is argued that RMC strength is probably more adversely affected by phenomena that inhibit good interfacial bond than is conventional concrete. Finally, it is concluded that much of the RMC currently placed is probably weaker than its mortar matrix but that an appropriate material specification and good site practice will go a long way towards ensuring that the compressive strength of RMC exceeds that of its mortar matrix.

Samevatting

Kriteria wat die swigtingsmeganismes, veranderlikheid en sterkte van messelpuinbeton (MPB) bepaal, word ondersoek met verwysing na die gedrag van gelyksoortige partikulere samestellings. Raakvlakpartikelinteraksie en die potensiaal vir anisotropie word genoteer as twee onderskeidende eienskappe wat baie van die materiaal se unieke gedrag kan verklaar. Swigting blyk begin te word deur delaminering van die klip-mortelraakvlak parallel aan die hoofspanning lank voordat die monsters maksimumspanning bereik het. Veranderlikheid van die meganiese eienskappe is bevind om 'n funksie van anisotropie en heterogeniteit te wees. Alhoewel die raakvlakoppervlakarea (tussen fases) in MPB ten minste 10 keer kleiner is as in konvensionele 19 mm klipbeton, word getoon dat dit nie hand aan hand gaan met 'n toename in raakvlakbindspannings nie. Daar word nogtans aangevoer dat MPB-sterkte waarskynlik meer nadelig beïnvloed word deur verskynsels wat goeie raakkvlaksterkte verhoed as wat die geval is met konvensionele beton. Laastens word daar tot die slotsom gekom dat baie van die MPB wat huidiglik geplaas word, waarskynlik swakker is as die mortelmatriks, maar dat 'n gepaste materiaalspesifikasie en goeie terreinpraktyk aansienlik sal help om te verseker dat die druksterkte van MPB die sterkte van sy mortelmatriks sal oortref.

Introduction

Knowledge of a material's strength pro[illegible] the basis for sound rational design. Without it, the designer has no idea of a structure's margin of safety against failure and the only available means of predicting the reliability of a new design is by reference to the precedent of another similar structure. Appreciation of a material's behaviour and variability under stress is equally important, since it enables the designer to assess the consequences of overload and apply an appropriate factor of safety to reduce the risk of catastrophe to an acceptable level without excessively compromising a structure's financial viability.

Ironically, in our advanced technical age, we still do not appear to have an adequate reference to the strength of rubble masonry concrete (RMC), despite it probably being the oldest man-made particulate composite building material on earth. This lack of knowledge is most certainly due to the difficulty of testing a material of such coarse heterogeneous texture, a problem appreciated by engineers and geologists throughout the world who have wanted to measure the properties of natural conglomerates (D'Elia et al, 1988; Lindquist and Goodman, 1994). The strength of most other materials can be simply derived experimentally by dividing the load required to break small representative prismoidal specimens by the relevant cross-sectional area of each specimen. However, to establish the mechanical properties of RMC requires extremely large specimens and heavy loading apparatus, since its boulder inclusions are typically bigger than even the largest conventional test specimens.

Given the mechanical properties of the constituent phases, their volumetric proportions, distributions and orientations, it may one day be possible to deduce a particulate composite's mechanical properties. For example, Volpe et al (1991) have suggested that the strength of a melange mass (body of stronger rock in a weaker matrix) can be represented by the weighted average of the strengths of the weaker matrix and the stronger inclusions, based on their volumetric proportions. However, such an attempt may produce serious discrepancies. An analogy between two elements and their chemical compound may be useful here. As is well known, when two elements combine to form a chemical compound, the latter acquires characteristic properties of its own that seldom bear any resemblance to either of the constituent elements. Thus, since this approach has no theoretical basis, it would appear to be a far cry from practical reality. For the time being, results from large-scale tests will probably yield more acceptable data.

Designers have been primarily concerned about this material's strength and behaviour under compression. Compressive strength is a property that is relatively easy to verify and that is readily understood and accepted by designers and contractors alike. Furthermore, it has been argued that, since brittle materials essentially always fail in tension, regardless of whether their loading is compressive, shear or tensile, data obtained from uniaxial compressive tests might also be used to gain some indication of their tensile properties and behaviour (Shah and Slate, 1968; Powers, 1978). Therefore, the understanding of RMC's properties and behaviour under compression seemed an obvious point of departure.

Failure mechanisms in concrete and natural conglomerates

Before dealing with the specific case of RMC, it may be useful to review existing understanding of the behaviours of analogous materials such as conventional concrete and natural conglomerates. It is well established (Newman, 1968; Dantu, 1958) that within particulate composites under a predominant load, localized 'bond' stresses develop at the interfaces between the inclusions and the matrix to facilitate the transfer of load between the softer phase (usually the matrix) and the stiffer phase (usually the inclusions). The magnitude of these bond stresses depends on the difference in stiffness between the two phases and the extent of any discontinuity of the matrix-inclusion interface (Newman, 1968; Dantu, 1958). The softer, more yielding matrix distorts to shed its load to the stiffer inclusions, resulting in localized stress concentrations at the phase interfaces, within the inclusions and in the matrix between inclusions in the path of the principal stress. Newman (1968) confirms this in his description of work done by Dantu (1958), who measured localized strains on the surfaces of concrete specimens, under an applied uniaxial compression, by a photo-elastic technique. Dantu found that strains in the softer mortar phase were generally higher than those in the more rigid aggregate particles and that the maximum strain at the aggregate-paste interface was four to six times the average composite strain. The corresponding stress distribution, calculated from the elastic moduli of the two phases, indicated that the maximum stress in the aggregate was about 2,8 times the mean, whereas the maximum stress in the mortar was about 1,9 times the mean.

The effect of coarse aggregates on particulate composite strength

Conservative engineering practice has tended to limit particulate composite strength to that of the weaker matrix. Indeed, when working with bimrock (block-in-matrix rock) and bimsoils, it is universal engineering practice to design for the strength of the weaker matrix (Medley and Goodman, 1994). However, the question of whether a soft material (matrix) may be reinforced through the addition of particulate inclusions has resulted in the birth of a complex science. The hypotheses, experimental results and explanations of numerous researchers (Jones and Kaplan, 1957; Okajima, 1972; Davis, 1975; Conjeaud et al, 1980; Cottin et al, 1982; Addis, 1986; Lindquist and Goodman, 1994) who have pondered this question are difficult to reconcile and far from conclusive. Under particular circumstances, the addition of inclusions has been found to increase compressive strength, yet under others inclusions are reported to weaken the composite. For example, using the 10 per cent Fines Aggregate Crushing Test (10% FACT, SABS 842) as a measure of aggregate strength, Davis (1975) investigated the relationship between aggregate strength and the compressive strength of concrete. He concluded that the compressive strength of normal structural-grade concrete, made with conventional South African concrete-making aggregates (typically 10 per cent FACT of 160 kN and over), was not significantly affected by the crushing value of the aggregate. However, as the strength of the concrete increased, the strength and surface characteristics of these aggregates assumed a greater significance. In the manufacture of very high-strength concrete (80 MPa and over; water:cement ratios of 0,40 to 0,33), he found that strength and surface characteristics of aggregates become a factor, as evidenced by the mortar matrix component strength exceeding that of the concrete by 10 per cent or more. Furthermore, Jones and Kaplan (1957) studied the effect of adding coarse aggregate to mortar and found that for leaner mixes, the compressive strengths of concretes were usually greater than their pure mortar counterparts, but that this was not necessarily so as the strength of the mortar matrix approached that of the aggregate. These findings may be partly attributable to fracturing of the aggregate as observed by Conjeaud et al (1080) and Cottin et al (1982), who have noted that as the strength of concrete increases, the fracture path increasingly begins to go *through* rather than around the aggregate particles.

Okajima (1972) has gone further and demonstrated that composite strength increases as the volume fraction occupied by particulate inclusions increases, but adds the proviso that the stiffness of the inclusions must exceed that of the matrix. This is consistent with a similar test described by Addis (1986) where the cube strength of concrete was reported to increase by 15 per cent as the volumetric fraction of stiff aggregate was increased from 60 to 70 per cent.

Beyond the immediate ambit of concrete, Lindquist and Goodman (1994), in a study of natural melange[1] behaviour, have noted that in order to afford the composite greater strength, the strength of the inclusion phase needs to exceed that of the matrix by a minimal margin. This conclusion followed a series of triaxial load tests on physical model melanges with the block (inclusion) and matrix phases made from cement-fly ash and cement-bentonite mixtures respectively, so that the inclusions were only twice as strong as the matrix. In accordance with the observations of Okajima and Addis, the compressive strength of these melange specimens was found to increase as the volume fraction of the stiff inclusions increased. They attributed this increase to an increase in the internal angle of friction, consequent upon the failure surface becoming more tortuous (it has to fail around more inclusions) at higher inclusion proportions. However, below a threshold of 30 per cent the presence of inclusions appeared to have little effect on strength. This observation is consistent with the previously undemonstrated hypotheses of D'Elia et al (1988) and Savely (1990) of a minimum inclusion threshold for melange and conglomerate respectively. Evidence of a similar threshold has been observed in heterogeneous soils. Based on a review of soil literature and some of their own work, Irfan and Tang (1993) have proposed a threshold volumetric inclusion proportion of 25 per cent for heterogeneous soils. Finally, Lindquist and Goodman's results (1994) also show that the orientation of the longitudinal axes of the inclusions with respect to the principal stress may have a profound effect on composite strength. In their case, the most adversely orientated inclusions had an inclination of 30° with respect to the principal stress and subsequently the lowest cohesion. This corroborates the assertions of Jaeger (1960) and Donath (1964) that anisotropic material should exhibit strength anisotropy.

Despite their triaxial nature, the phenomena shown to affect melange strength in Lindquist and Goodman's tests may also apply to man-made particulate composites such as RMC under 'uniaxial' load. Considere (1906), Richart et al (1928) and Gardner (1969) have all reasoned that any theory capable of predicting the behaviour of granular cohesive material

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1 *Melange:* French word for a mixture of relatively large inclusions within a matrix of finer and weaker texture

can be applied to concrete. Therefore, they postulate the strength of concrete under triaxial stress may be equal to its 'unconfined' failure strength plus a constant times the confining pressure. However, it should be borne in mind that, beyond some threshold, the confining pressure in a triaxial test will probably have the effect of improving the toughness of the mortar matrix by suppressing crack growth and making it behave as a ductile, rather than a brittle material. Nevertheless, assuming that these triaxial phenomena may be applied in a less confined case, it does not appear that large suspended aggregates require great strength to afford additional compressive strength to the composite, provided the strength of the inclusions is at least marginally greater than that of the matrix. The magnitude of this margin (to prevent failure through the inclusions) does not appear to have been accurately established and may be specific to individual cases. However, in Lindquist and Goodman's case a factor of only two proved sufficient.

The effect of size of inclusions upon compressive strength

From the cracked hulls of Liberty Ships, which broke at surprisingly low stresses, to the filaments (whiskers) of glass-fibre strands, which break at higher stresses as they get thinner, there are many examples that lead to the conclusion that material strength decreases as specimens get bigger. Concrete specimens (containing aggregates of a constant size, ie not scaled in proportion to the specimen dimensions) appear to follow this law, as evidenced by many researchers (Rajendran, nd; Gonnerman, 1925; Higginson, 1963; Krishna Raju and Basavarajaiah, 1979), who have discovered that the crushing strengths of small concrete cube specimens exceeded the strengths of their larger counterparts. Numerous authors (Walker and Bloem, 1960; Higginson, 1963; Bloem and Gaynor, 1963) have also shown that the tensile strength of concrete decreases as the nominal coarse aggregate size increases. However, it will be shown that size effect phenomena do not necessarily apply .. the case of an increasing nominal particle size in a predominantly compressive stress field.

The United States Bureau of Reclamation (Higginson, 1963) and Walker and Bloem (1960) used large-scale cylinder tests (up to 48 inches long by 24 inches in diameter – 1 220 mm by 600 mm) in an effort to explore the effect of maximum size of aggregate (up to six inches – 150 mm) on the compressive strength of concrete used in structures such as Hoover Dam. Their results confirmed a relationship that for a given water:cement ratio, strength decreased as aggregate size increased. However, they noted that this phenomenon only became pronounced as the matrix became stronger, in which case failure appeared to be initiated by a parting of the two phases at their interfaces. It seems reasonable to deduce that this relationship is probably only marginal for concretes other than high-strength grades, since other reports by Bloem and Gaynor (1963) and Higginson et al (1963) conclude that the compressive strength of structural and lower grades of concrete is little affected by the size of stone used in the mix. Unfortunately, none of these studies provide satisfactory explanations. An increased proportion of entrapped bleed-water beneath the undersides of the larger aggregates, as noted by Hughes and Ash (1970), is unlikely to have made a significant contribution to this weakening, since cylinders are loaded parallel to the direction of casting and therefore perpendicular to planes of weakness created by bleed-water lenses.

Davis (1975) argues that: '*Large particles are responsible for high interfacial bond stresses owing to the limited surface areas available to accommodate bond forces* (to transfer load between phases). *Smaller sizes of aggregate, however, have greater specific surfaces and are therefore better able to transmit these forces.*' Presumably, Davis makes the assumption that the magnitudes of internal forces to be transmitted via these interfaces remain constant regardless of the nominal size of coarse aggregate. Hence, assuming this is true, it seems reasonable to speculate that aggregate surface phenomena, which may play a relatively minor role in affording strength to normal structural grade concrete (with relatively small aggregate), should become more critical when the specific surface area available for bonding with the matrix diminishes (as a consequence of using larger aggregate).

More recently, Baker (1996) has cautioned against the indiscretionate application of relative size-scale effects to particulate composites and has argued that aggregate effects cannot be scaled. '*Increasing the nominal size of aggregate may be expected to affect the mechanical properties of concrete by (1) influencing the development of micro-cracking (possibly as a consequence of higher interfacial stresses caused by a decreased surface area), (2) shielding the matrix by arresting or deflecting cracks, (3) making the failure "plane" more undular and (4) toughening the wake[2] zone.*'

2 Wake zone: The discontinuity left in the 'wake' of an advancing crack.

Baker reasons that by increasing the particle size (assuming idealised spherical particles), the radius of curvature of the path the crack is forced to follow is correspondingly increased. Theoretically, this would require less force to drive the interface crack and therefore decrease the apparent strength. However, in practice, with the exception of river rounded pebbles, aggregate particles are seldom round and spherical. The same sharp edges that occur as a result of the coincidence of fracture planes on small particles also exist on larger specimens of the same material. In short, sharp edges remain sharp, irrespective of scale. Thus, particulate composite materials are probably more sensitive to the curvature on the edges of these aggregates than their nominal particle size.

Relationship between the properties of the interface and the mechanical properties of the composite

The question of a direct link between interfacial bond strength and concrete strength has been the subject of much debate. Cracks in a heterogeneous material like concrete propagate in a direction that is near-perpendicular to the maximum tensile stress, but they also tend to follow the weakest path. Addis (1994) has proposed that the strength of concrete at failure (albeit compressive) may be analogous to the weakest link of a chain. His chain has three types of link: aggregate, aggregate-paste interface and hardened cement paste; failure occurs when the weakest link fails. Conventional wisdom has it that the aggregate-paste interfacial zone is the 'weak link' in concrete (Hsu et al, 1963; Le Chatelier, 1905; Sabin, 1905). Sabin (1905) pointed out that 'since mortars are usually employed to bind other materials together, it follows that adhesive strength is of the greatest importance'. Certainly, it is common to see fracture paths in ordinary concrete predominantly routed along the interfaces between the coarse aggregate particles and the matrix. Whether this is due to an inherent weakness of the interface, or to stress concentrations at these interfaces, or perhaps a combination of these two, remains to be clearly established.

Numerous studies (Alexander et al, 1965; Shah and Slate, 1968; Mindess et al, 1996; Struble et al, 1980; Mindess, 1989) have concluded that certain desirable properties of concrete, including compressive strength (Alexander et al, 1965), may be improved by increasing the interfacial bond strength. In practice, going from no bond to perfect bond, reported strength increases are not overwhelming but generally lie in the range of 15 to 40 per cent, with improvements in tensile strength being more significant than those in compressive strength.

Using a model to simulate the stress distribution around a single stiff aggregate particle in a soft cement matrix, Vile (1968) has postulated a most probable order of failure: (1) Tensile bond failure; (2) shear bond failure; (3) shear and tensile matrix failure; (4) occasional aggregate failure.

Summary

It would appear that the compressive strength of a particulate composite may be enhanced, beyond a minimum threshold, by the addition of inclusions that are stronger and stiffer than its matrix phase, provided a mechanism to transfer some minimum load between the phases exists. The phenomena affording this strengthening probably include the shielding or arresting of advancing cracks within the matrix, increased tortuosity of the failure surfaces, caused by the obstruction imposed by the inclusions, and toughening of the wake zone, as a result of the mechanical interlock formed by the undulating fracture surface.

Experimental exploration of RMC

Testing philosophy

There can be little doubt that RMC is probably the coarsest heterogeneous construction material ever used by man, and such is the nature of coarse heterogeneous materials that they tend to exhibit much variability of mechanical properties. Consequently, we need to draw conclusions from averaged data derived from large populations for each control variable tested. Unfortunately however, the very high cost of material transportation, customised mould fabrication, load press rental and rubble removal, associated with such large specimens, makes this prohibitively expensive. Therefore, it is imperative that the testing strategy be exceptionally well contrived to derive the maximum amount of useful experimentally derived information. Furthermore, it is prudent to first explore the extremes of control variables rather than attempt to measure subtle nuances, since the latter may well be obscured by the high variability.

Choice of testing technique

Traditional test cubes cannot accommodate even the smallest boulders used in RMC and are therefore inappropriate. A comprehensive literature search was conducted to explore the possibility of adopting some precedent to measure the strength of RMC. Unfortunately, there appears to be no record of any testing performed on a material with such large inclusions. Chamaly (1995) has advocated testing 'undisturbed' samples of RMC, to be obtained by coring the hearting masonry of dams, in an effort to establish its true character and strength in service. However, coring poses several practical difficulties. For example, the drilling resistance of each phase would be significantly different, possibly causing the harder material to become detached from the weaker matrix, thereby weakening the specimen sufficiently that it may lack the necessary tenacity to survive extraction. Furthermore, the costs of coring representative samples of RMC would be prohibitive, owing to the coarseness of its texture necessitating very large diameters. Consequently, a method of testing RMC had to be developed to explore and quantify phenomena that afford RMC compressive strength (Rankine, 1997).

Pilot study

A pilot study (SABS Method 863: 1976, 1976) was undertaken to gain a preliminary indication of the behaviour of RMC under compression and to explore a suitable procedure for further testing. As the order of strength of this material and the maximum size of its inclusions were unknown quantities at that time, three cubic specimens of different sizes were cast (300 mm, 400 mm and 500 mm). The 500 mm size was the largest that could be accommodated on the hydraulic press (Amsler 500 t, Switzerland) at the University of the Witwatersrand and, weighing about 300 kg, this specimen size bordered the threshold of manageability given the available resources. At full force, this press could crush the 500 mm specimen provided it was weaker than 20 MPa. Cubic shape specimens were cast because they optimally utilize the platen area available and because they could be conveniently cast in plywood moulds. The specimens were all cast by the same labour force and with the same materials used to build an RMC bridge in the Northern Province. The specimens were cured in their moulds, indoors to preclude thermal shock damage, for 28 days before testing. The test results are presented in Table 1 and the 28-day strength of the mortar matrix (derived by crushing 100 mm cube specimens) was 14,93 MPa. The 500 mm cube size was subsequently adopted for all further uniaxial strength testing because smaller cubes were unable to accommodate the bigger boulders.

Table 1: RMC strengths measured in the pilot study

Cube size (mm)	*28-day strength (MPa)*
300	14,0
400	9,0
500	9,6

Development of a proposed test for exploring parameters governing the behaviour of RMC loaded in compression

Based on the testing experience from the pilot study, trials with other specimens and a review of literature on the development of concrete compression testing, a procedure for testing RMC was developed. A comprehensive description of this proposed test method and its evolution is presented elsewhere ((Rankine, 1997). In essence, the test utilizes 500 mm cubic specimens to accommodate the largest boulders typically used (smaller cubes could not accommodate them). Parameters that might influence the apparent compressive strength, such as geometric tolerances of forms, platen texture and speed and concentricity of loading, are standardized to enhance repeatability and reproducibility.

Testing of cubic test specimens to explore the effects of increasing inclusion size

Fifteen 500 mm cubic specimens were cast and tested in accordance with this procedure (Rankine, 1997) to explore the effect of inclusion size on the strength and variability of RMC in compression. Quarried Olifantsfontein dolomite with clean, freshly fractured surfaces was collected, sorted and stockpiled into three size fractions according to particle mass. The smallest fraction (1 kg to 4 kg) was chosen to border the threshold of the minimum size typically used, the intermediate fraction (7 kg to 15 kg) represented a size that felt most comfortable to handle and the largest fraction (25 kg to 40 kg) was deliberately selected to border the upper threshold typically used in practice. A transit mixed batch of mortar with a W:C ratio of 0,84 and a collapse slump made with straight Portland cement (no extender) and coarse sand (FM > 3) was delivered to ensure consistency of the matrix. A series of 100 mm test cubes was cast to establish the conventionally derived mortar strength and also to establish the size scale effect of the large specimens. The fifteen 500 mm cubes were divided into five series of three specimens per series. The first series of three 500 mm cubes was cast with pure mortar (without any inclusions) to establish the size scale effect and its variability. The second, third and fourth series contained inclusions of the smallest, intermediate and largest fractions of rock respectively. The fifth series contained inclusions of the largest and the smallest fractions of rock packed in such a way that the smaller particles occupied some of the interstitial volume between the larger particles, as is now the custom in southern Africa. Cubes were packed by helpers who were instructed to maximize the content of stone and minimize the air voids. Thereafter, the specimens were cured in their moulds, indoors to prevent thermal shock damage, and tested after 28 days on the same 500 t press used during the pilot study (shown in Fig 1). The results are presented in Table 2.

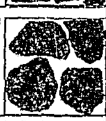
Observations

A comparison of the volume fractions of rock inclusions (expressed as percentages in Table 2) shows consistency at around 42 per cent in the case of specimens containing single-size aggregate fractions. This consistency provides a favourable basis with which to isolate the effect of inclusion size without concern for the need to account for possible extraneous phenomena as a consequence of different inclusion volume fractions. Several noteworthy observations are listed below.

1. The exceptionally low variation of the 500 mm mortar cube strengths ($\sigma/\bar{x} < 1\%$) provides some assurance of the consistency of the mechanical properties of the matrix.

2. The reduction in apparent strength as a result of size effects phenom-

Table 2: Test data of fifteen 500 mm cube specimens. Relative surface areas are relative to the interfacial surface area of the series containing the largest inclusions and are therefore dimensionless. Specific surface areas were calculated assuming a shape factor of two (ie assuming the dolomite inclusions had surface areas twice as large as single equivalent spheres of equal volume).

Series	Single equivalent nominal particle Vol. (dm^3) & (Diam. mm)	Specimen number & Statistical data	Strength (MPa)	Volume fraction of rock (%)	Relative surface area (dimension less)	Estimated surface area of inclusions (m^2/m^3)
1		1	9,240	Nil		
		2	9,164	Nil		
		3	9,340	Nil		
		$\bar{x}$	9,25		-	-
		σ	0,09			
	No Rock	$\sigma/\bar{x}$	0,93%			
2 		4	10,024	41,4		
		5	10,088	42,0		
		6	10,228	42,4		
		$\bar{x}$	10,11	41,9	2,34	42
	0,9 dm^3	σ	0,10	0,5		
	(120 mm)	$\sigma/\bar{x}$	1,03%	1,2%		
3 		7	13,940	41,4		
		8	12,808	45,2		
		9	12,768	39,6		
		$\bar{x}$	13,17	42,0	1,44	26
	3,9 dm^3	σ	0,67	2,9		
	(195 mm)	$\sigma/\bar{x}$	5,05%	6,8%		
4 		10	14,088	39,7		
		11	14,404	40,6		
		12	12,600	46,4		
		$\bar{x}$	13,70	42,2	1	18
	11,6 dm^3	σ	0,96	3,6		
	(281 mm)	$\sigma/\bar{x}$	7,03%	8,6%		
5 		13	11,328	56,4		
		14	15,680	57,3		
		15	10,648	49,8		
		$\bar{x}$	12,55	54,5	1,3	24
	11,6 & 0,9 dm^3	σ	2,73	4,1		
	(281 & 120mm)	$\sigma/\bar{x}$	21,75 %	7,5%		

Notation	28 day 100 mm mortar cube strengths (MPa)	
	1)	15,07
$\bar{x}$ = mean	2)	14,84
σ = standard deviation from the mean	3)	14,74
$\sigma/\bar{x}$ = coefficient of variation from the mean	$\bar{x}$	14,79
expressed as a percentage of the mean	σ	0,3
	$\bar{x}/\sigma$	2,0%

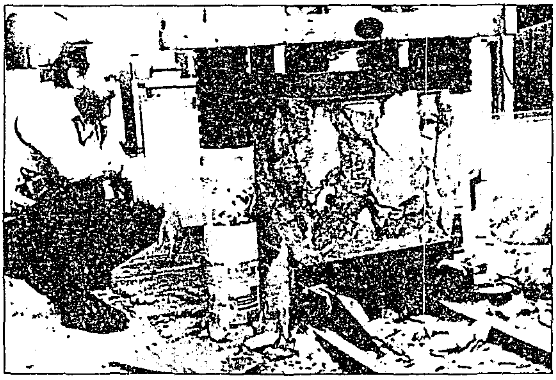


Fig 1: A 500 mm RMC specimen (approx 300 kg) undergoing a compressive test under the 500 t Amsler press at the University of the Witwatersrand

ena (and possibly also different testing machine characteristics) appears significant; the mean 500 mm mortar cube strength is less than two thirds of that of the 100 mm mortar cubes.

3. The incorporation of rock increased the strength without exception by between nine and 48 per cent (based on statistical analysis of averaged strengths).
4. In series 2 to 4, the mean composite strength increased as the nominal size of rock inclusion increased.
5. In series 2 to 4, the variation in strength within each series increased as the nominal size of rock inclusion increased.

Typical sequence of events leading to the disintegration of RMC under compression: A generalised sequence of events leading to the disintegration of specimens was noted in all testing to date. Initially, RMC appears to exhibit symptoms of distress similar to conventional concrete. At a load of between 70 and 90 per cent of maximum, visible hairline cracks running sub-parallel to the principal stress appear. As the load increases to maximum, these cracks widen and coalesce with other cracks. At this stage, the widest cracks tend to form near to the edges and often an entire edge of mortar will become detached, as shown in Fig 2. Examination of these detached mortar surfaces reveals almost clean breaks (often a slight grey discolouration is left on the rock surfaces) between the rock face and the matrix, indicative of tensile or shear bond failure.

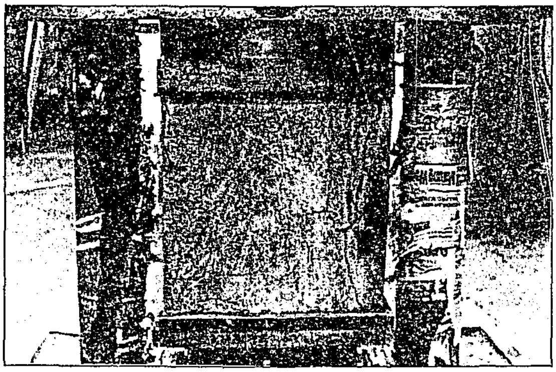


Fig 2: Typical vertical crack parallel to the principal stress at about maximum load

Beyond maximum load, the specimens usually disintegrate in the classic hourglass shape, analogous to the failure of a concrete cube. However, as previously mentioned, the rock inclusions in RMC frequently bear contiguously upon their adjacent neighbours. In all specimens but those containing the weakest mortars, these points of contact caused severe and audible shattering of rocks (see Figs 3 and 4) owing to bearing stress concentration.

Fig 3: Fracturing of rock caused by very high local stresses as a consequence of boulders bearing against one another at points of contact (left: quartz vein; right: Olifantsfontein dolomite)

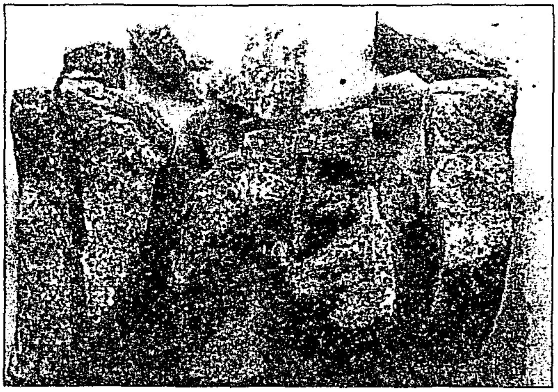


Fig 4: Fragments of the same quartz vein rock illustrated in Fig 3 showing the extent of fracture.

Discussion

Variability

Comparison of the coefficients of variation within the first four series of tests, presented in Table 2, confirms that variability of both inclusion volume fraction and strength increases as inclusion size increases. This is to be expected as a consequence of testing a constant volume of an increasingly coarse and heterogeneous material, since the bias evolved by a particularly favourable or unfavourable orientation of a single inclusion is more likely to distort the experimental outcome as the number of inclusions per specimen decreases. Therefore, the coefficients of strength variation in the fourth and fifth series are likely to be exaggerated and conservative. If the ratio of specimen size to inclusion size was increased, more realistic (lower) variations in strength could be expected. Nevertheless, these four recorded values are all low and acceptable within the range normally designated for concretes (Rankine, 1904).

An anomaly is the disparity between the coefficient of variation of the fourth series (seven per cent) and the much higher coefficient of the fifth series (22 per cent), more than a threefold increase. To date, a satisfactory explanation for this has not availed. This is unfortunate, since the fifth series is the one most representative of the constitution of RMC used in practice. Furthermore, these specimens were cast under idealised conditions from a single batch of mortar to eliminate the influence of as many extraneous factors as possible. RMC cast on site is likely to depend on mortar that has been crudely batched, with little or no control of its W:C ratio. Therefore, in practice, even higher variability may be expected. Roxburgh (1997) reports the results of nine tests by the same testing procedure (Rankine, 1997) in a parallel study. These specimens were cast under adverse circumstances during the final stages of construction of a dam in Mpumalanga. The stockpile of rock was contaminated with mud and heavy rain flooded the works, making control of the mix's water content between batches difficult. The corresponding coefficient of strength variation recorded between three specimens in a series was 30 per cent.

Surface phenomena

As discussed previously, interfacial bond and coarse aggregate size are not deemed to contribute overwhelmingly to the compressive strength of conventional concrete. In the case of aggregate size, this may be because the increase in specific surface area (the total inclusion-matrix interfacial area in a given volume) is not exponentially affected by changes in nominal inclusion size. The specific area of a given volume of particles increases in linear proportion to particle length. Thus, by halving the linear dimensions of a given volume of particles, their specific area doubles. On the corollary, we need to reduce the particle volumes of granular materials by eight times just to double the specific surface area. This is illustrated in the context of a cube in the example in Fig 5, but is true regardless of particle shape, provided the material retains its fractal nature.

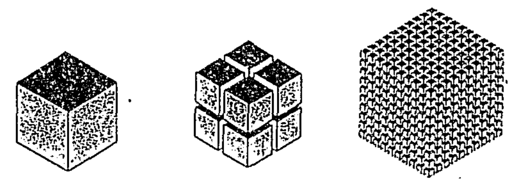


Fig 5: The linear relationship between particle size and surface area. A cube 1 m long exposes a surface area of 6 m^2 (A). Dividing this 1 m cube into eight smaller cubes, each with linear dimensions half as big as the former, doubles the surface area to 12 m^2 (B). Dividing it into 1 000 smaller cubes (C) each with linear dimensions a tenth as big (compared to A) increases the surface area by one order of magnitude. Although the model illustrates the phenomenon in the context of cubic particles, the relationship holds true, regardless of shape, for all materials exhibiting a fractal nature.

Table 2 illustrates this relationship for the case in point. The estimated specific surface (the area of the inclusion-matrix interface in 1 m^3 of RMC) was calculated by multiplying the surface areas of the appropriate number of equivalent spherical volumes (that is equivalent to the known nominal volumes of the three size fractions used) by a shape factor of two. The number two is probably realistic of the dolomite in question, but is insignificant in the outcome of this argument, since only the relative relationships are important. By assigning a relative surface area of one to the composite containing the biggest nominal particles (11,6 dm^3, in series 4) as a basis for comparison, we see that a more than twelve-fold volumetric decrease (to 0,9 dm^3) is needed to increase the relative surface by only 2,34 times. Extrapolating this relationship to the size of aggregate commonly used in concrete (say 19 mm), we see a significant difference in relative surface areas (19 mm aggregate has a surface area about 15 times larger than the reference 11,6 dm^3 fraction) and at least ten times the surface area of conventional RMC (consisting of big and small inclusions). Therefore, if interfacial bond stresses did increase in inverse proportion to the decreasing specific surface area (as the particle size increased), then the strength of RMC should be less than its equivalent concrete strength by about one order of magnitude. The reason that this is not the case is because bond failure is a tension-shear type failure and the area of such a fracture surface is not much affected by aggregate size, as illustrated by the path lengths of the two hypothetical fracture surfaces in Fig 6. Assuming the composite in question consists of cubic particles with weak links at their joint surfaces, then it is of no consequence to the path length (from A to B) whether the particles are big or small. However, the more undular surface may be better able to resist sliding.

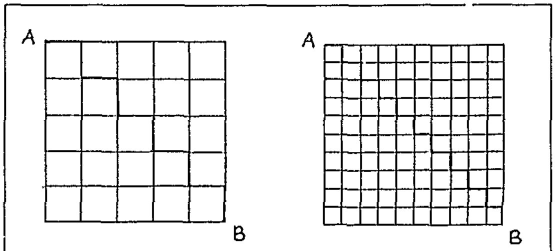


Fig 6: Hypothetical models representing parts of an infinite matrix containing regular cubic particles. Assuming tension-shear failure occurs only at the 'weak link' joints, it can be seen that the fracture length from A to B is independent of the particle size.

Notwithstanding this fact, interfacial bond in RMC is probably more critical than in conventional concrete. Firstly, there is likely to be a greater inherent tensile stress (caused by factors such as drying shrinkage and thermal strains) within the mortar matrix between inclusions, since these mortar volumes become greater as the nominal particle size increases while the inclusions remain rigidly held because of their contiguity with adjacent neighbours. Secondly, any bond discontinuity will affect a relatively large area, thereby placing greater stress on the adjacent continuity. Examples of phenomena that have been observed to inhibit good interfacial bonding in RMC include the following:

1. *Lens-shaped cavities formed due to the entrapment of bleed-water as it becomes trapped against the undersides of large particles* (see Fig 7). In severe cases, the migration of bleed-water may also interrupt the bond at the sides of particles. In such cases, the mortar surface near the interface exhibits a glassy appearance.

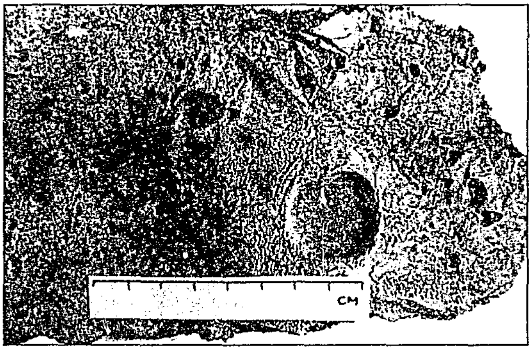


Fig 7: The upper surface of a layer of mortar de-bonded by a lens of bleed-water trapped against a flat horizontal under-surface of dolomite rock. Large stones are more disposed to trap bleed-water on its upward migration to the surface, particularly if their lower surfaces are horizontal or cupped. The presence of the lenses effectively de-bonds the phases at their interface.

2. *Powdery substances that form on the surfaces of some igneous rocks* (such as basalts, dolerites and gabros) as a result of their chemical weathering. The products of their weathering include clays that preclude the paste from bonding with the coherent underlying rock surface. An indication of the extent to which this poor bond can reduce composite strength may be evidenced by comparing strengths from the pilot study (Table 1) with the fifth series in Table 2. The specimens in Table 2 contained freshly quarried rock with excellent bonding characteristics, whereas those of the pilot study (Table 1) contained an assortment of hand-gathered colluvium, including a large proportion of dolerite. The surface of this dolerite had chemically weathered and developed a powdery skin containing illite and montmorillonite clays that could be rubbed off with finger pressure and felt slippery when wet. Fracture of the specimens containing this weathered-skin-dolerite seemed to be initiated by bond failure at these powdery interfaces at a very early stage and the dislodged boulders appeared to have suffered much less distress than the other rock types. In many instances, remnants of this powdery surface remained in the cavities of the matrix after the stones had been dislodged, as illustrated in Fig 8.
3. *The contamination of any sound surface by dirt.* This usually occurs by rain water splashing mud against rocks in contact with the ground and the consequences are illustrated by Fig 9.

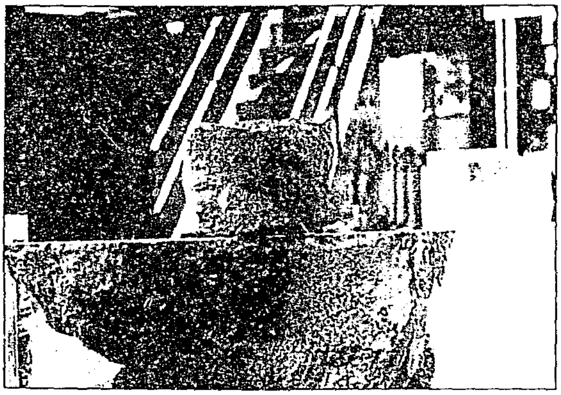


Fig 8: The dolerite boulder sitting on the cube became detached at low stress as a result of poor bonding characteristics with the matrix. Dolerite weathers chemically into illite and montmorillonite. This is undesirable because it forms a weak powdery substrate that inhibits a strong bond between the matrix and the sound underlying rock. The poor adhesion may be evidenced by a mustard-coloured powdery residue now attached to the cavity left in the mortar matrix.

Fig 9: A lack of adhesion to good freshly quarried granite caused by its contamination with mud

Orientation of rocks

That anisotropic rock exhibits anisotropic mechanical properties appears to be well recognized in rock mechanics (Lindquist and Goodman, 1994; Jaeger, 1960). RMC is inherently anisotropic, owing to the natural tendency for flat and/or elongated inclusions to lie horizontally. Elongated rocks that are oriented parallel to the principal stress axis tend to split the matrix apart by a cleaving and wedging action (see Figs 10 to 12), whereas the same shape rocks, oriented perpendicular to the principal stress, are effective in tying the matrix together.

In an effort to demonstrate how different-shaped inclusions precipitate fracture, two idealised brass inclusions were cast suspended in the centre of a transparent polyester cube. The inclusions were machined into equivalent cones in such a way that although their angular proportions were very different, their surface areas were identical (see Fig 11). Once the polyester had solidified, the two specimens were loaded in tandem (one on top of the other), parallel to both cones' longitudinal axes. As anticipated, the specimen containing the more slender cone, with sharper points, precipitated the first fracture surfaces, sub-parallel to the principal stress, radiating away from the inclusion. However, before the crack could be photographed, this specimen exploded violently. The experiment was repeated with near frictionless polyethylene platen surfaces and a transparent polyethylene safety barrier. This time both specimens exploded simultaneously and ruptured the barrier. In the interests of safety, further testing with this brittle polyester matrix was aborted. Tougher high-clarity (transparent) epoxy resins have subsequently availed, but their high

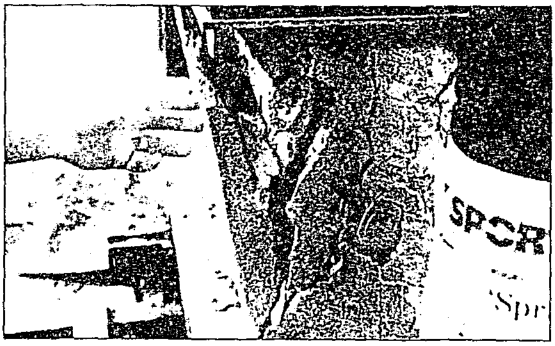


Fig 10: Typical wedging-cleaving failures caused by sharp inclusions orientated parallel to the principal stress

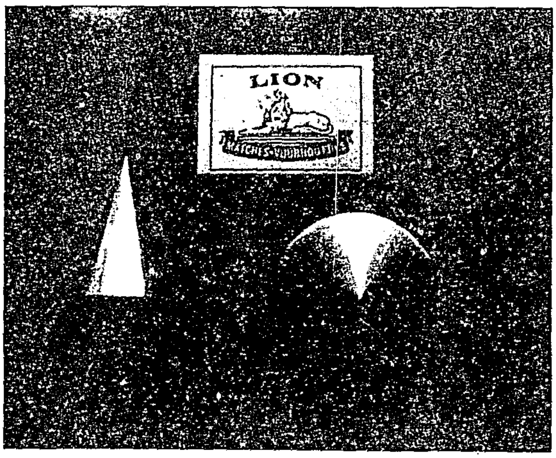


Fig 11: Different-shaped inclusions modelled as equivalent cones in brass; both with equal surface area. These cones were cast, centrally suspended in a transparent polyester matrix, and then loaded in tandem, parallel to their longitudinal axes. The more pointed cone precipitated the first fracture, sub-parallel to the principal stress, but shortly thereafter exploded, discharging the matrix as shrapnel.

cost makes their use difficult to justify in this instance.

Fig 12 shows a simplified schematic representation of post-bond equilibrium forces of such an idealised conical inclusion. The radial splitting component increases as:

1. The angle b decreases since the inclusion wedges the matrix apart with greater leverage and/or
2. The component of friction at the matrix/inclusion interface decreases and/or
3. The ratio of stiffness between the inclusion and the matrix increases

However, the relationship between these factors is extremely complex. For example, as the angle b increases and the inclusion's surface becomes orthogonal to the principal stress, the frictional component simultaneously increases as a result of the increased bearing pressure at the slip face. This is what affords flat stones, placed perpendicular to the principal stress, the ability to tie the matrix together.

The contribution made by mortar matrix strength

Sims (1994) has stated that as the richness of a lime mortar increases from a ratio of lime to sand of 1:5 to 1:3 the strength of RMC is increased, but that insignificant further benefit is derived if the mixture is made still richer. This appears to have been corroborated by Roxburgh (1997), who explored the relationship between matrix strength and RMC composite strength using Portland cement mortars and freshly quarried granite. In the case of low-strength mortars (4 MPa to 5 MPa), he found that the measured strength of the RMC specimens was about the same as the measured strength of their 100 mm mortar cube counterparts. In cases of higher-strength mortars (16 MPa to 18 MPa), the measured RMC strength was only about 60 per cent of the strength of the 100 mm mortar cube counterparts. Thus, at higher mortar strengths, the effect of a change of mortar strength on composite strength was less significant than at low mortar strengths. Unfortunately, Roxburgh was unable to explore material with a crushing strength greater than 20 MPa, because until recently equipment available to this research initiative has not been capable of testing 500 mm cubes stronger than 20 MPa.

Relative size considerations

Increasing the size of inclusions within a given volume, either in a specimen or in a structure, has both positive and negative implications concerning the composite's compressive strength. Table 3 presents a list of some of these effects. The relative significance of the different effects may depend upon specific individual circumstances.

The most significant effect, as evidenced by this initiative and work by Bazant (1984), is the ratio of specimen size to inclusion size. Large inclusions confine greater volumes of mortar by way of frictional constraint as shown in Fig 13(a). In cubic test specimens, large inclusions afford confinement to the dilating matrix, particularly if part of them is embedded in the triaxially confined zone shown as a shaded area in Fig 13(b). In a limited volume, such as a test cube, this may add significantly to the constraint already offered by the platens. This is why concrete testing specifications (BS 1881: Pt 108, 1983; SABS Method 863: 1976, 1976) limit the ratio of specimen size to aggregate size to a maximum. Unfortunately, limitations in available testing equipment have made compliance with this requirement impossible in testing RMC to date. To date, the biggest inclusions tested had a diameter more than half the size of the cubic specimen length. Thus, this large-inclusion confining effect is probably responsible for a substantial proportion of the apparent strength gain between series two and four. A future project might aim to quantify this strengthening effect by comparing the measured strength of another similar series of specimens, containing the same size fractions, but loaded against near-frictionless platens. Alternatively, if significantly larger testing facilities avail, the size of specimens could be increased to comply with conventional concrete testing constraints. However, for the time being, it would be prudent to assume that RMC may, at best, be only slightly stronger than its mortar matrix and that its properties may be highly variable.

Table 3: A list of phenomena that may affect particulate composite strength as the size of the inclusions increase

Strengthening effects	*Weakening effects*
1. Greater confining potential within a small volume	1. Higher contact stresses as an inverse function of the number of rock contacts per unit volume
2. Increased tortuosity of the failure surfaces resulting in a more undular wake zone with deeper interlock to better resist shear and sliding	2. Greater entrapment of bleed-water by larger obstacles
3. Greater capacity to shield and arrest advancing cracks	3. Less surface area for interfacial bond
4. Lower density of 'weak link' critical flaws and potential crack initiation interfaces	4. [illegible]s energy is required to drive cracks around the larger radii of ideal rounded particles
	5. A greater number of flaws exist within the rock inclusions

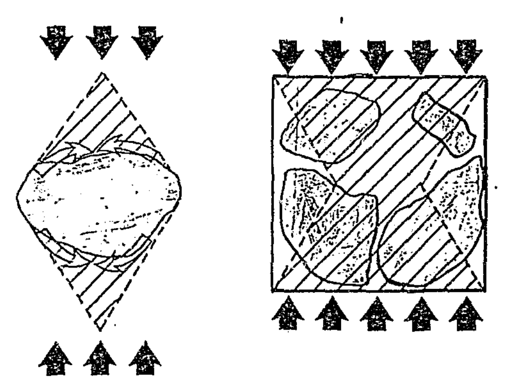


Fig 13: Triaxially constrained areas as a result of friction between the matrix and the inclusion surface (a). Triaxially confined zone (shaded) within a test cube that is capable of anchoring portions of large aggregates that project beyond it into the 'unconfined' zone (unshaded) (b)

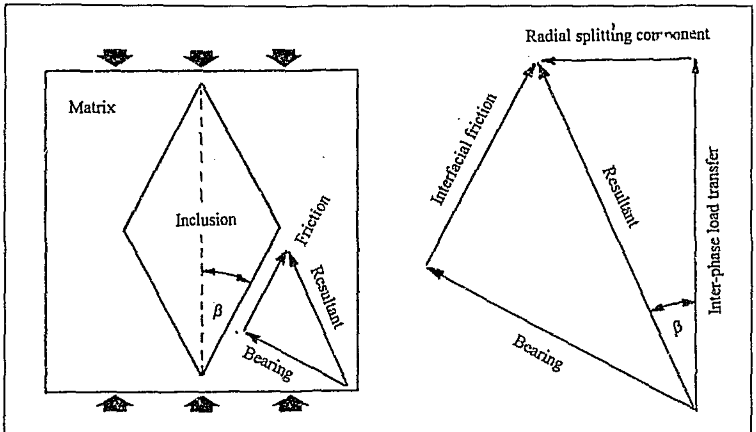


Fig 12: Simplified schematic representation of post-bond equilibrium forces around an idealised axially symmetrical suspended conical inclusion.

Conclusion

The variability of cubic RMC specimen properties, containing uniform size inclusions, appears to be a function of their heterogeneity, expressed as the ratio of nominal inclusion size to specimen size. Although strength appears to increase significantly with increasing inclusion size, it is likely that this phenomenon arose predominantly as a consequence of the relatively small specimen size. Consequently, unless satisfactory evidence to the contrary avails, it will be prudent to assume that RMC used in service will not exhibit as much strength as these 500 mm cubic test specimens.

RMC composite strength appears to derive more benefit from an increase in mortar strength at low mortar strengths than it does at higher mortar strengths.

Local discontinuities between the phases caused by contaminated rock surfaces, bleed-water lenses and trapped air pockets appear to initiate general parting of the phases. Thereafter, failure appears to be governed by mechanisms that form between boulder inclusions. Rock fracture, as a result of high bearing stresses, is common where contiguous boulders interact and bear upon their adjacent neighbours. These bearing stresses appear to increase with increasing boulder size and stiffness. Elongated inclusions have an observed tendency to split, wedge or cleave the mortar matrix apart when their longitudinal axes lie near-parallel to the principal compressive stress.

The uniaxial compressive strength of RMC appears to be affected by the orientation of elongated and/or flat inclusions with respect to the principal stress. As a result of this strength anisotropy, the predominant horizontal placement of boulders, which is inherent in most RMC structures built in recent times, is likely to significantly reduce their potential strength (particularly in arch structures). However, by simply altering the current practice of placing boulders, this strength anisotropy could be exploited to engineering advantage.

Acknowledgements

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Written discussion on the technical papers in this issue of the *Journal* will be accepted until 31 May 1999. This, together with the authors' replies, will be published in the Fourth Quarter 1999 issue of the *Journal*, or the issue thereafter. For the convenience of overseas contributors only, the closing date for discussion will be extended to 30 June 1999. Discussion must be sent to the Directorate of SAICE.

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