CHAPTER 170

ASSESSING THE EFFECT OF ARMOURSTONE SHAPE AND WEAR

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ABSTRACT

Impacts, abrasion and physico-chemical weathering which sometimes result in rapid changes of armour shape and size can have disastrous consequences for armour stability. This paper draws together the background ideas and some new techniques which have been developed to tackle the prediction of weight loss and shape change of rock armourstone during the life of a coastal structure.

The framework proposed is to measure separately the wear resisting material properties of a rock type using a tumbling mill simulation of prototype block degradation. Time on the structure is then related to mill time by a factor which accounts for initial block size and the site specific environmental conditions. A field site in Scotland is used to demonstrate the new image analysis methods for measuring rounding of prototype blocks. The shape analysis results can also be used to calibrate the equivalent wear factor for conditions at that site. Discussion of this framework is extended to dynamically stable design concepts where abrasion losses are faster.

Preliminary flume testing in collaboration with H. R. Wallingford indicates that losses in stability due to rounding could be considerable.

INTRODUCTION

It is widely acknowledged that the occurrence of sources of rock with favourable geotechnical properties of rock in areas close to sites requiring slope protection against wave attack will guarantee the widespread use of rock armoured designs into the foreseeable future. By reviewing recent progress with techniques of measurement, this paper sets out to demonstrate that for natural armourstone, both block shape and the effect of wearing processes could be important design considerations and a way forward for taking these into account is suggested.

The paper is in three parts. The first provides the background, and presents the reasons for measuring shape and wear of armourstone. The second part summarizes the laboratory techniques for simulating prototype wear and measuring weight loss and shape changes, the details of which have been published elsewhere. In the third part, photography of block outlines from a Scottish case study are used to indicate abrasion rates. These form the basis of discussion of the implications for loss of stability of rounded rocks in the light

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of recent flume experiments which were designed to investigate the effect of shape and rounding on stability.

BACKGROUND

Armourstone Degradation

The problem of rock degradation is not restricted to coastal engineering. In highway construction, (for example) to aid the selection of appropriate rock for road aggregate, Lees & Kennedy (1975) gave an account of mechanisms of degradation. In their paper, disintegration processes were considered according to the ratio of the size of the broken product to the size of the original particle. Although informative, their discussion is only partly applicable to the special demands of rock armourstone. Fookes et al. (1988) have recently attempted an extensive review of rock weathering in engineering time but again its applicability to armourstone wear is limited.

For riprap and armourstone, Lutton et al. (1981) reported details of project experience from 38 Corps of Engineers offices in the USA. The deterioration phenomena were classified as cracking, spalling, delaminating or splitting (of foliated rock), disaggregation (of granular poorly cemented rock), disintegration (due to unavoidable occurrence of shaly or weakened rock) and dissolution. Almost half the offices reported no degradation problems in the past 10 years to 1979 and, even though it was concluded that improved testing and geotechnical supervision could further reduce problems and achieve economies, degradation problems were generally considered relatively insignificant.

In recent years, with port expansion in areas where only poor quality rock is available, there has been growing interest in degradation problems. The mechanisms of wear and degradation of rock in the marine environment have been studied in Australia, the Middle East and the UK by Poole and various co-workers. Recommendations from their field and laboratory studies were reported by Fookes & Poole (1981), Dibb et al. (1983a,b), Poole et al. (1984) and Allsop et al. (1985). They identified catastrophic fracture, abrasion and spalling as the three classes of degradation mechanisms. The presence and nature of anisotropy, pre-existing cracks, joints and discontinuities in the rock fabric of an armour block are all important considerations, particularly since they may result in numerous block failures while handling during construction. However, further discussion, is concerned primarily with wear processes.

The disruptive forces driving the decay process which have a complex, often cyclic and stochastically varying time history, are set against the cohesive forces that the rock fabric can harness.

The static loads of the block weights give compressive and tensile stress concentrations depending upon block shapes, contact areas and settlements. With tensile strengths of rock at least ten times lower than compressive strengths, tensile cracking is much the commonest catastrophic failure mode under severe dynamic loads.

Abrasion due to attrition of suspended material is a type of high frequency dynamic indentation which leads to loosening of fragments along pre-existing cracks, cleavage planes and grain-boundaries and, to chipping resulting from lateral vent tensile cracks forming sub-parallel to the surface during unloading. It is not surprising therefore that Verhoef et al. (1984) were able to show a correlation of volume loss due to sand blasting with Brazilian tensile strength. On prototype armour, the size, velocity and hardness of the impactors and their density in the water jet will influence the attrition wear rates.

The larger dynamic forces occur during construction and while rocking, rolling and sliding during storms. These can result in major breakages creating new projectiles as well as shear and tensile mode cracking on all scales down to the rock grain size. In addition to impact forces, the more gradually varying wave forces produce a pulsating form of load cycling. Both types promote the subcritical extension of tensile microcracks by the two mechanisms, stress corrosion and cyclic fatigue (see Costin and Holcomb, 1981).

The physico-chemical processes, whether salt crystallisation, hydration, differential thermal expansion or wetting and drying, can all induce cyclic pressure fluctuations which undoubtedly contribute to subcritical growth of tensile microcracks and eventual spalling of surface layers. Another cause of cracking and spalling could be the relaxation of residual tectonic stresses, an effect which can be measured using overcoring methods.

To summarize, it has been argued that wear processes at the armourstone surface, whether due to abrasion from external impacts or to disruptive pressures (e.g. from salt attack) within cracks and other surface openings, are essentially restricted by cohesive forces measured by the subcritical and critical indices of fracture toughness of the rock (which express its resistance to crack extension). Consider now the factors governing the rates of armourstone wear (i.e. weight losses) on coastal structures.

Rates of Wear

Rates of rounding were shown (Dibb et al., 1983a) to depend on the horizontal zone on the structure being considered because of the different energy associated with the various abrasion and physico-chemical forces at different positions relative to the still water level. The rates of armourstone wear as measured by the percentage of original weight remaining after a given number of years is likely to show a dependence on initial block dimensions since the rate of mass removal by abrasion is closely related to block surface area. The main factors governing wear rates on a new structure are:

(i) size of armourstone;
(ii) wave energy characteristics;
(iii) zone on structure;
(iv) size and type of water-borne attrition agents;
(v) climatic influence on physico-chemical degradation mechanisms, e.g. temperature range, rainfall, humidity;
(vi) local slope of armour layer - affects proportion of stone area exposed to attack;
(vii) armourstone displacement tolerated in design concept;
(viii) resistance of rock fabric to disaggregation under applied forces - a function of rock type and its degree of weathering.

Effects of Wear Processes

The effects of wear are to cause rounding, weight loss and some changes in void characteristics within the armourlayer surface. The number of point contacts with neighbouring blocks may even increase. The net effect will usually result in increased mobility of blocks and could possibly lead to instability. There may be a positive feedback here since increased mobility with significant rolling displacements of perhaps a few diameters per year, will further assist and accelerate wear.

Within the framework of Van der Meer's classification of rock slope structures (see Fig. 1), wear introduces two potential problems to the engineer. The first concern will be the reduction of interlock for conventional statically stable breakwaters. As the expected block mobility, crudely quantified by the dimensionless wave height parameter $H_s/\Delta D_{n50}$, is increased, a second concern becomes the weight loss. H_s is the significant wave height, Δ is the relative mass density and D_{n50} is the nominal diameter of the median armour weight. For structures with $H_s/\Delta D_{n50}$ approaching values as high as 20, seasonal profile adjustments can result in blocks moving up and down the slope depending perhaps on the timing of storms in relation to the tide cycle. The increased mobility that can result from rounding is not likely to be particularly threatening to the self-adjusting structure unless the weight losses due to size reduction and rounding become particularly marked and along-slope movements are considerable. As berm and S-shaped breakwaters and rock beach designs are increasingly being considered because of the possible economic advantages of their smaller block sizes, it is important to consider whether the increased mobility is likely to affect the performance and integrity of the structure and, if so, in what time scale. Additionally, it should be noted that the overall rate of weight loss is faster for smaller armour blocks because in relation to their weight they have comparatively high surface area.

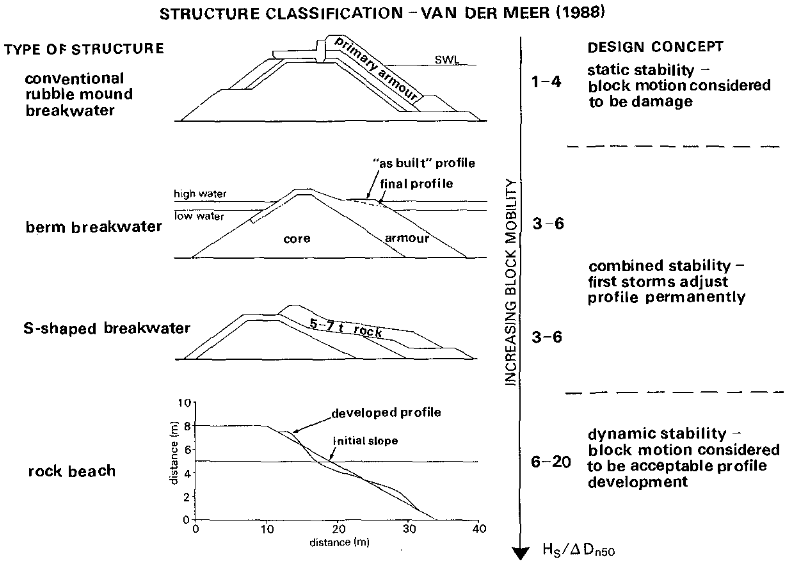


Figure 1: Types of rock armoured structures

Shape and its Controlling Factors

By shape, and in relation to armourstone, engineers will usually mean the gross shape which is often given by the axes of the enclosing cuboid. Most of the form indices such as flatness and sphericity are ratios of the X, Y and Z axes. In this paper, shape is taken to include the gross or overall shape but with details of the roundness of the corners together with the surface texture superimposed on and between the corners.

Factors at the quarry tend to govern the gross shape while those on the breakwater are a result of wear, and influence the roundness and surface texture.

The quarry may have been opened in a massive igneous intrusion yielding more equant blocks or alternatively, in a bedded sedimentary sequence giving more tabular blocks. If the rock is foliated or anisotropic, it may be impossible to obtain equant blocks with $X/Z < 2$. These are the geological controls. The structural geological setting which influences discontinuities and joint patterns as well as quarrying methods will also influence block shapes. The selection criteria (for example the exceedance value of the X/Z ratio) can also influence what is to be stockpiled and what rejected or re-blasted at the quarry.

Factors controlling block shape on the breakwater have already been discussed in relation to wear processes.

Design Implications of Block Shape

It should be stressed that it is placement technique in combination with block shape that is important in the performance of the breakwater.

For statically stable designs, interlock, macroporosity and thickness of the armour layer, which are all functions of shape are going to affect hydraulic stability. In fact, macroporosity and thickness both appear in Van der Meer's design equations through their influence on the permeability coefficient. The shape also influences hydraulic efficiency, i.e., reflection, transmission and run-up, although this may be of lesser significance.

Probably the main reason for rejecting rocks with higher X/Z ratios is a structural one. Tabular and elongate shapes, for example, have a lower resistance to fracture in bending because of the higher bending moments than for cubic blocks. However, there is some evidence emerging from the flume (see Table 1 and later discussion) that tabular blocks may have hydraulic advantages due to their higher resistance to rolling.

Purpose of Shape Quantification

To evaluate shape effects on static stability and hydraulic efficiency and thereby to improve specifications has been an overall objective of this current research. A related objective was to develop a laboratory simulation and a theory of abrasive wear in-service so that the wear during the life-time of a structure could be assessed for different rock types.

The whole question of shape effects could not be tackled with the conventional methods of shape quantification using the Krumbein/Wadell measure of roundness. The new techniques are described in a later section but first some of the evidence for the effect of rounding on static stability is reviewed.

Evidence of Shape Effects on Stability

Jensen (1984) presented two sets of results from random wave tests, one for 'quarrystone' and one for rounded 'seastones'. A lower stability was noted for rounded tests although the two sets of test conditions appear to be different, making objective comparison difficult.

Bergh (1984) using an impermeable core, composite profile and irregular waves, found that for the start of damage $H_s/\Delta D_{n50}$ was 50% lower for rounded glacial boulders than for cubic rock, implying an 8-fold increase in stone weight required for the rounded to achieve the same stability.

Van der Meer (1988) did not consider gross shape and roundness as test variables for static stability. However, significant abrasive rounding in his long test programme was suggested as a possibile explanation of certain results. (For example, for surging waves, was generally 35% lower for the older and presumably rounded test material). These explanations have been vindicated by recent research to be reported in Latham et al. (1988).

The Shore Protection Manual suggests that a different stability coefficient K_D should be used for smooth rounded rock and rough angular quarrystone. However, no clear guidance to the designer on shape effects is currently available.

It was noted that when, investigating dynamic stability, Van der Meer (1988) concluded that stone shape had no or only minor influence on the profile developed when for relatively permeable core conditions.

TECHNIQUES

Mill Abrasion Test

The mill abrasion test uses coarse aggregate pieces of crushed rock and was developed with the apparatus shown schematically in Fig. 2. For reasons set out in Latham & Poole (1987b) a number of features have been introduced which distinguish it from other tumbling mill abrasion tests used for aggregates. For example, there is a constant water level and throughput of water carrying fines and chippings away in suspension. The bulk volume fraction of the mill cylinder is always kept between 0.5 and 0.4 as the successive increments of milling are followed by making up the weight losses with fresh material. The abrasion is relatively gentle and there are no steel balls in the mill. Keeping the abrasion/attrition environment relatively constant in this way means that any non-linear response of weight or shape with time in the mill is not an artefact of non-linear test conditions. Rather, it is a reflection of the behaviour of angular particles becoming rounded and smaller while they cascade across the dimetrical free surface on each revolution. It is these weight loss and shape change relationships that are of interest in the study of wear.

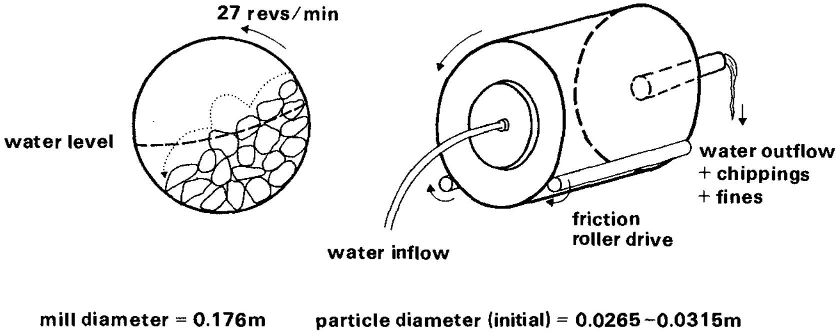


Figure 2: The tumbling mill abrasion test apparatus

The fraction of the original weight remaining when plotted against revolutions in the mill can be analysed to give two exponential coefficients, one of which is ideal for measuring and thus classifying the abrasion resistance of different rock types.

The experimental reproducibility was demonstrated using Carboniferous limestone aggregate in Latham & Poole (1988) and is reproduced in Fig. 3 together with the equation and coefficients describing the weight loss with time relationship. The coefficient k_S is the abrasion resistance index which can be used to describe the durability of the rock. The variation in test results for different rock types from a tough granite to a soft muddy limestone is indicated in Fig. 4. The values of k_S, indicated by the slopes, vary by about 2 orders of magnitude for the range of rock types likely to be encountered in coastal engineering works.

To examine the change in roundness or roughness of the blocks inside the mill, the image analysis techniques of the modern sedimentologist have proved invaluable.

Image analysis of block shape

The Fourier shape analysis methods of Ehrlich & Weinberg (1970) offer the best method for quantifying the rounding of blocks. Suppose the thin line in Fig. 5 is the outline given by the digitized coordinates (e.g. from a video camera). These coordinates can be represented by a Fourier series. The more terms or harmonics used in the series, the better the representation becomes. By the time the 10th term has been added see Fig. 5(d), the approximation, though quite good, is generally smoother than rough outlines with surface texture. To describe a rough irregular outline more precisely, the 11th to 20th harmonics are needed. In fact, the sum of the 11th to 20th harmonic amplitudes gives a very good measure of roughness, which was discussed with several other shape descriptors in Latham & Poole (1987a) and later given the name Fourier asperity roughness factor P_R where

$$P_R = (0.5 \sum_{20}^{n=11} C_n^2)^{0.5}$$

and C_n is the amplitude coefficient of the nth harmonic.

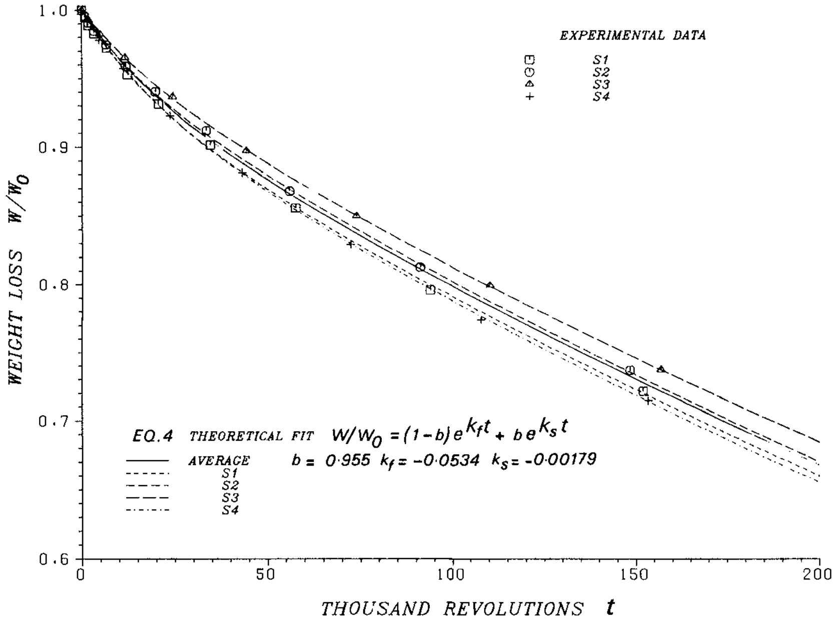


Figure 3: Reproducibility of mill abrasion test results from four limestone sample

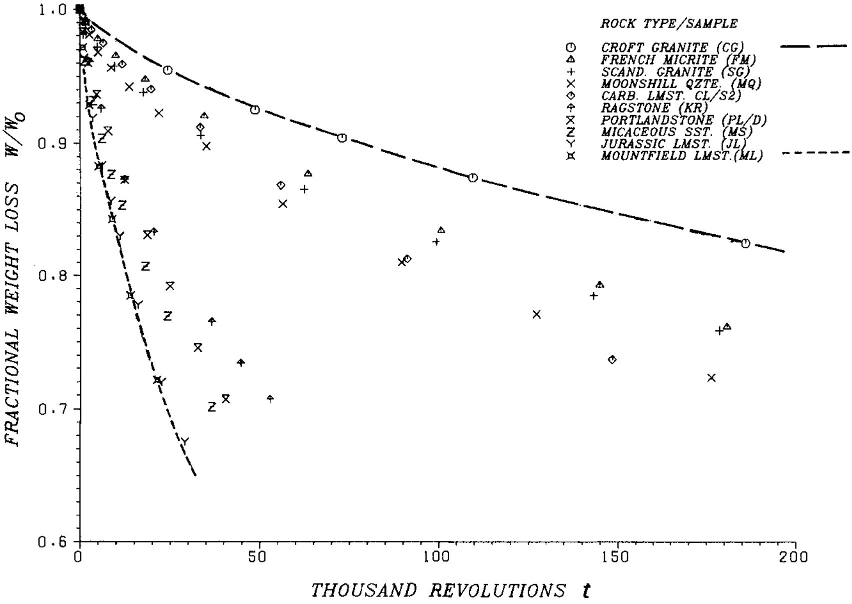


Figure 4: Variation of mill abrasion test results with rock type

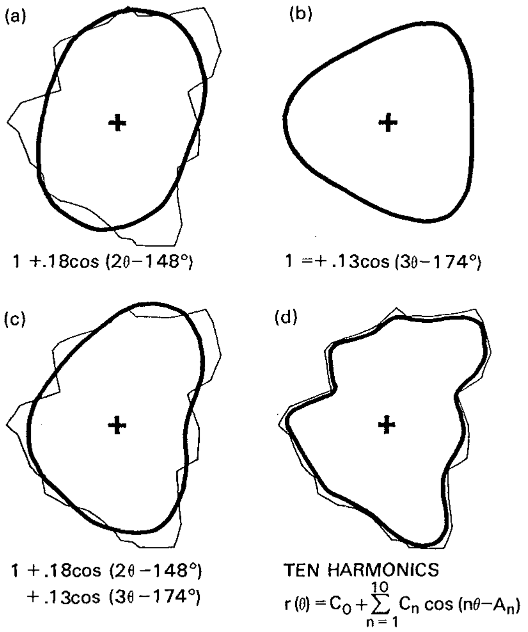
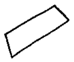


Figure 5: Contribution of Fourier harmonics to shape, after Ehrlich & Weinberg (1970)

	QMC/HR					DHL
AVERAGE SHAPE DESCRIPTOR VALUE	 TABULAR	 FRESH	 EQUANT	 S.ROUND	 V. ROUND	 EQUANT
Gross shape						
X/Z	3.23	2.22	1.82	2.19	1.92	1.7
P_C	2.67	1.88	1.43	1.89	1.55	
Roughness						
P_R	.0165	.0138	.0117	.0097	.0046	
V d Meer Coeff. surging formula	1.32 (7)	- (3)	1.19 (8)	1.10 (8)	0.95 (8)	1.0

$$\boxed{H_s/\Delta D_{n50} = \underset{\uparrow\ \text{COEFF}}{1.0}\, P^{-0.13}\,(S/\sqrt{N})^{0.2}\sqrt{\cot\alpha}\;\xi_m^P}$$

Table 1: Shape descriptor results for different armour shapes used in flume tests. A preliminary evaluation of a shape effect on stability is also shown.

A range of typical values of the Fourier shape descriptors is given in Table 1. The five shape classes were those tested for static stability in the flume at Hydraulics Research

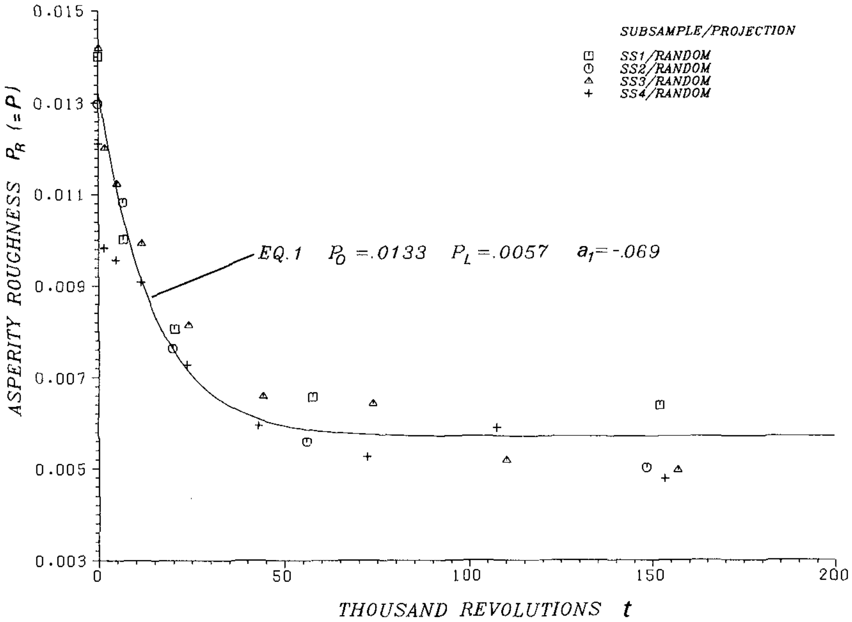


Figure 6: Roughness reduction during mill abrasion

Ltd. Each sample contained 48 blocks and the projections of the blocks were taken at random orientations to the video camera. Note P_C which indicates gross shape, is about 80% of the X/Z ratio for all 5 shapes. The asperity roughness P_R is very sensitive to the abrasive rounding. When FRESH material was put in the abrasion mill, after a 7% weight loss, P_R had fallen from 0.0138 to 0.0097 and after 23% weight loss, the VERY ROUND value was 0.0046.

Mill Abrasion Theory

To describe what is happening inside the mill, two assumptions are made. First, that a roughness parameter P will have the limiting exponential form

$$P - P_L = (P_0 - P_L) \exp(a_1 t) \qquad (1)$$

during progressive abrasion where P_0 and P_L are initial and limiting (i.e. large t) values of P, a_1 is a constant and t is measured in thousands of revolutions of the mill. Second, that the instantaneous rate of weight loss is given by how much roughness there is left for removal and by the fraction of the original weight remaining, which yields the differential equation

$$\frac{d(W/W_0)}{dt} = a_2 (P - P_L) + a_3(W/W_0) \qquad (2)$$

The solution is $$W/W_0 = \frac{a_2 (P_0-P_L)}{(a_1 - a_3)} \exp(a_1.t) + \left\{1 - \frac{a_2(P_0 - P_L)}{(a_1 - a_3)}\right\} \exp(a_3.t) \qquad (3)$$

which is the same form as the equation given in Fig. 3 for quantifying the abrasion resistance k_s from the weight loss results. It was expressed as follows

$$W/W_0 = (1 - b) \exp(k_f.t) + b \exp(k_s.t) \qquad (4)$$

The consequence of equating these coefficients using experimental data and curve fitting to test the validity of the assumptions turns out to be favourable since a_1 is approximately equal to k_f. It appears then, that the weight loss can be directly related to shape changes when the roughness P is described by the asperity roughness P_R. For the two exponential coefficients in equation (4), k_f is the smoothing resistance index which describes the rate of the fast process of removing asperities and k_s, the abrasion resistance index, describes the rate of the slow process of overall size reduction, (b is a mixing term). Eliminating t produces an equation for W/W_0 in terms of asperity roughness.

$$W/W_0 = (1 - b)\left(\frac{P - P_L}{P_0 - P_L}\right) + b\left(\frac{P - P_L}{P_0 - P_L}\right)^{k_s/k_f} \qquad (5)$$

A more detailed theoretical development was given in Latham & Poole (1988). Fig. 6 has been taken from that paper to illustrate the fit of equation (1) to the abrasion mill data for four Carboniferous limestone samples.

A new concept is now introduced so that the laboratory information and theory of the mill abrasion test can be applied beyond simple rock durability assessment.

Equivalent Wear Factor

The great number of factors that affect the rate of wear on the prototype breakwater was indicated earlier in this paper. It is suggested that all the site specific and environmental factors should be combined together and kept separate from the rock durability and that the implicit assumption be made that the progress of prototype rounding, for a given rock type, is equivalent to that which occurs inside the mill for that same rock type but that it occurs at a different rate. The EQUIVALENT WEAR FACTOR X to relate these laboratory and prototype rates was defined (Latham & Poole, 1988) as the number of years of exposure at a particular zone on a given structure that is equivalent to 1000 revolutions in the tumbling mill test described in the reference. However, in that paper, the authors neglected to point out the need also to separate the initial block weight from the combined site specific factors. The effect that initial block size will have on rate of weight loss is conveniently taken into account assuming the volume to surface area relationship. For example, if the rate of removal of two different sized blocks with the same shape is initially governed by their surface areas, then for an 8-tonne block which after 1 year loses, say, 0.20 tonnes ($W/W_0 = 0.975$), a 1.0 tonne block loses 0.05 tonnes ($W/W_0 = 0.950$) which is a faster rate of fractional weight loss. For a given set of site specific factors, the equivalent wear factor x will depend on the size of the prototype blocks. In Latham & Poole (1988), the suggested values of x were based on observations of rounding where the armourstones were nominally 8 tonnes. To adjust for a different initial block weight W_n in tonnes, the equivalent wear factor x becomes $(W_n/8)^{1/3}$ times its value for an 8-tonne block. Clearly a suggested value of x should refer to a particular initial block weight.

From the data obtained on statically stable breakwaters in N.E. Queensland, the Middle East and the U.K., for the most aggressive environment in the intertidal zone, a value of x = 0.5 was suggested for 8 tonne armour. Table 2 shows how the mill abrasion test data for Carboniferous limestone can be used to predict wear rates (both weight loss and rounding) on statically stable structures built with 8-tonne Carboniferous limestone armour. For example, a 12% weight loss ($W/W_0 = 0.88$) would occur between 25 and 50 years in service for a relatively aggressive environment with x = 0.5 to 1. A smaller value of x implies a faster rate of wear.

Field evidence from West Bay, Dorset, reported by Clark (1988) is discussed in the report (Latham et al., 1988), where it was concluded that aggressive conditions with shingle attack corresponded to an x value of about 0.8 for 8-tonne armour.

The image analysis techniques can be applied to armour blocks from real structures. This allows for a direct measurement and comparison of the shapes and relative states of rounding of different armour blocks to be made. The results obtained can be used to help calibrate x for different site conditions as demonstrated below.

Weight loss	Asperity roughness	Revs in mill (thousand)	Equivalent Wear Factor for W_0 = 8 tonnes		
			Mild x = 5	x = 1	Aggressive x = 0.5
W/W_0	P_R	t	Years on breakwater		
0.97	0.0102	10	50	10	5
0.94	0.0083	20	100	20	10
0.88	0.0062	50	250	50	25
0.80	0.0057	100	500	100	50

Table 2: Application of the equivalent wear factor concept to Carboniferous limestone armour

APPLICATIONS

Rounding of Whin Sill Dolerite from Buckhaven, Scotland.

This revetment structure was constructed in 1975 and was reported to have been designed at a 1 in 2 slope and built with 1 to 2-tonne armourstone quarried from the Whin Sill dolerite. It is underdesigned in that storms frequently cause rocks to roll down onto the foreshore. It is one of the only U.K. examples of a structure resembling a rock beach where block mobility and shingle attrition have combined to produce dramatic rates of wear against perhaps one of the most durable rock types in the U.K. A typical angular block and a well rounded block were shown in Allsop & Latham (1987). Digitized outlines of 8 upper blocks and 8 lower blocks are shown in Fig. 7.

Although these block outlines are not statistically representative samples, for illustration the upper block values may be equated with the initial condition during constrution and the lower block values with 12 years' wear. The gross shape parameter P_C has hardly changed while the asperity roughness P_R has falled from 0.0149 to 0.0062. Mill abrasion results were not available for this rock type but it is known to have a very high fracture toughness ($K_{1c} \approx 3\text{MPa.m}^{0.5}$) and density ($\approx 3.0$ tonnes/m^3).

On this basis and comparing with test results for the toughest granites, an estimate of the abrasion resistance index and other mill abrasion constants can be calculated. Applying the mill abrasion theory outlined above with the available measured and estimated data suggests that 50,000 revolutions in the mill would give the observed P_R value of 0.0062 and at a weight loss of 9%. The equivalent wear factor x for these semi-mobile blocks of about one tonne is therefore 12/50 = 0.25. However, for 8-tonne blocks, the value would be 0.5.

It might be expected that equivalent wear factors on dynamic structures would be lower (i.e. faster wear) than for statically stable structures. It is possible then that the value of 0.5 for 8-tonne blocks which was suggested in Latham & Poole (1988) for extremely aggressive environments on statically stable structures is slightly too low and is more representative of a structure which has included some mobility in the design concept (e.g. $H_s/\Delta D_{n50} \approx 6$).

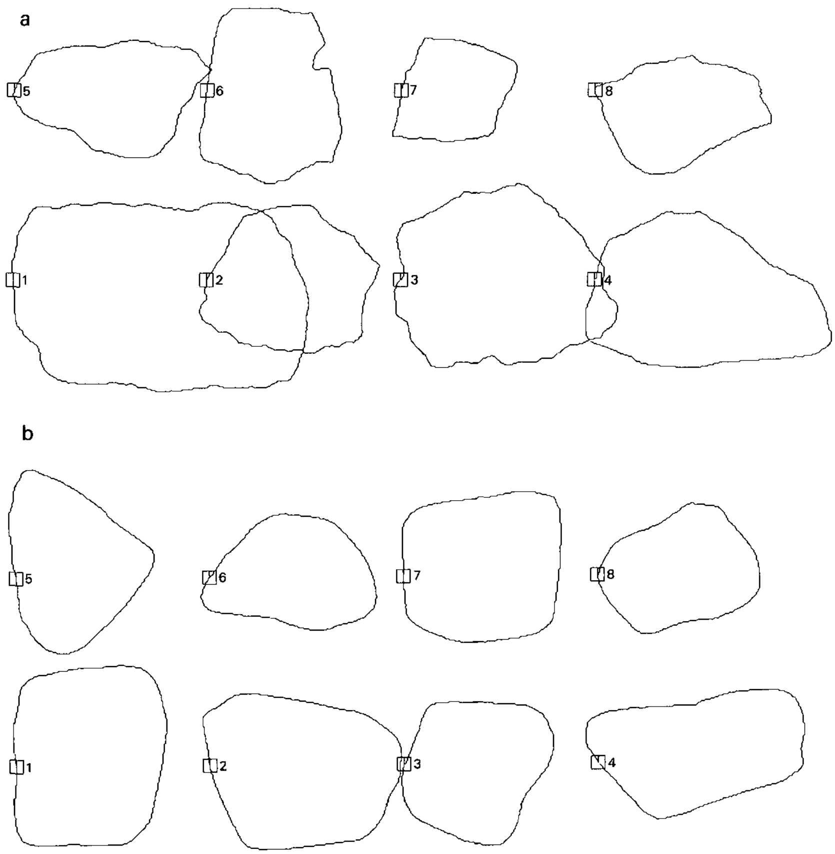


Figure 7: Digitized outlines of blocks from Buckhaven; a upper, b lower

Discussion

As a working hypothesis, it is reasonable to suggest that the material property measured by the resistance to weight loss inside the tumbling mill over, say, one day will rank different rock types correctly in terms of their weight loss performance over perhaps 10 years of episodic wear on a breakwater. The validity of the equivalent wear factor concept used in the prediction of in-service rates of wear is more tenuous and requires further validation in the future. The concept assumes that the non-linear equations (1) to (4) for mill abrasion also apply to prototype abrasion.

Two likely objections to this are (i) that wear mechanisms, particularly those of subcritical crack growth, not properly represented in the abrasion mill may contribute to the form of the non-linear relationship on the prototype; (ii) that, while the work done per unit time is kept relatively constant in the mill, the average work done by disruptive forces on each armour block of a dynamic structure (where there is a gradual increase in block mobility due to rounding) may increase with time, thus having an accelerated effect on weight loss rates.

In response to these legitimate criticisms: (i) it was noted that the Allison and Savage (1976) prototype weight loss data gave essentially the same type of relationship observed for abrasion inside the mill; (ii) the equivalent wear factor concept provides a framework which takes account of two of the most important reasons for relative differences in wear rates, namely material properties and initial block sizes. The framework can be refined and calibrated by future observations and tests; (iii) The relationship in equation (5) is time-independent so that, for blocks undergoing attack on all sides, it is possible to predict weight losses directly from shape changes measured on a prototype structure; (iv) for dynamic structures, the problem may be more complex although in some respects the mill simulation is more appropriate. It may be fruitful to consider Van der Meer's (1988) treatment of dynamically stable profile development in a search for the likely influence of armour block mobility on the choice of x. For structures with $H_s/\Delta D_{n50} \leq 6$, the acceleration effect of increasing mobility on wear rates may be negligible. For structures with $H_s/\Delta D_{n50} \geq 6$, a question to address is how many block diameters does the average block roll per year and does this distance depend on block shape?

Flume Test Results on Rounded and Angular Material

For static stability, the consequence of weight loss on armour stability can be calculated using Van der Meer's (1987) design equations. To predict the effect of rounding on static stability, the limited series of flume tests conducted in collaboration with Hydraulics Research Ltd, Wallingford, can provide some tentative guidance. The flume tests first reported by Bradbury et al. (1988) were intended as a preliminary series to evaluate shape effects on stability. For each different shape of rock tested, the results were fitted to Van der Meer's surging wave equation. Where Van der Meer obtained a coefficient value of 1.0, the flume tests found this coefficient, and therefore the stability, to be dependent on shape. For instance, the coefficients (see Table 1) suggest that the very round rock gives $(1.19/0.95)^5$ or 3 times more damage than the equant rock. The asperity roughness appears to account for the shape effect on stability reasonably systematically. For statically stable designs, the tests suggest that the loss of interlock due to rounding contributes more to instability than the weight loss itself accompanying the rounding. These aspects of the flume tests will be considered in detail in the report by Latham et al. (1988).

ACKNOWLEDGEMENTS

The authors wish to express their thanks to William Allsop for collecting photographs from Buckhaven and for his interest in this research. The paper has benefited from certain points raised during discussion by one questioner for which we are grateful. The research was funded by the Science and Engineering Research Council of Great Britain under grant GR/D/69921.

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