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REVIEW OF CONCRETE RESISTANCE TO ABRASION BY WATERBORNE SOLIDS

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ABSTRACT

In the last four decades, numerous investigations have been undertaken on abrasion-erosion of concrete using various test methods. These have suggested existence of different abrasion mechanisms, limitations of existing test methods and inconsistencies on the importance of compressive strength to abrasion resistance of concrete. The objective of this review is to: understand the mechanisms of concrete abrasion-erosion, assess the suitability of existing test methods to simulate field conditions and investigate the relationship between abrasion resistance and compressive strength. It is found that concrete abrasion mechanisms are dependent on both transport modes of abrasive charge and the ratio of coarse aggregate to matrix hardness. The ASTM C1138 (underwater) test method appears to simulate all the critical modes of sediment induced abrasion expected in field conditions and specific energy can be used as a framework to correlate ASTM C1138 test results with field measurements. With the exception of concrete with rubber aggregates, abrasion loss is found to fit a simple power function of its compressive strength, and no significant improvements in abrasion resistance can be gained by using concretes with compressive strengths exceeding 60 MPa (8.70 ksi). Also, the influence of cementitious additives and coarse aggregate properties is only significant at compressive strengths below the optimal value of 60MPa (8.70 ksi).

Keywords: concrete abrasion; coastal structures; durability; hydraulic structures; resistance models

INTRODUCTION

Abrasion-erosion is a major form of deterioration in concrete structures exposed to the action of water flows incorporating hard sediments. Although silt and sand sediments can also cause some degree of concrete abrasion-erosion damage, severe damage occurs when coarse sediments defined on the Wentworth scale[1] as pebbles (2-64 mm [0.0788-2.520 in.]) and cobbles (64-256 mm [2.520-10.086 in.]) are transported at velocity by the flow[2,3]. Its effects on structural performance include reduced safety, reduced durability and increased operating costs arising from regular repair requirements. Many past studies summarised in the recent report of ACI Committee 207[4] have strongly focused on abrasion-erosion of stilling basins of hydro-electric dams and other riverine structures for which abrasion loss depths of up to 2 to 3 m (6 to 10 ft.) have been reported. However, this type of damage also poses serious maintenance challenges for concrete structures situated in the coastal environment with coarse beach sediments[2,3]. **Figure 1** shows a revetment-seawall junction at Rossall, Fleetwood in the North West of England exhibiting severe abrasion-erosion with exposed steel reinforcement and sheet piles which are also heavily abraded. This particular damage was caused by the action of rounded pebbles and cobbles (also termed as shingle) driven by breaking ocean waves[3]. Indeed, the exposure of embedded metal components creates suitable conditions for the onset of secondary structural degradation processes such as chloride-induced corrosion[3]. Concrete abrasion-erosion depths shown in **Table 1** underscore the significance of this problem in coastal structures. In fact, for both stilling basins and coastal structures constructed in severe abrasive environments, attainment of the typical 100 year design service life can be jeopardised, more so in the absence of a robust maintenance programme. Furthermore, the fact that repair of abrasion-damaged surfaces are expensive operations costing millions of dollars[5] exacerbates the consequences of abrasion-erosion.

When abrasion-damage in stilling basins was arguably first problematized in the USA in the 1950s[6], damaged surfaces were repaired using various materials without any evaluation of their relative abrasion performance. The repair materials used included conventional, fibre-reinforced, and polymer-impregnated concretes. As expected, the different repair materials used exhibited markedly varied degrees of effectiveness[5]. These findings highlighted the importance of developing laboratory test methods for rapidly evaluating the relative performance of materials proposed for construction or repair of hydraulic structures[5].

In the last four decades, several test methods outlined in **Table 2** have been developed, and used in numerous studies to investigate concrete abrasion mechanisms and influencing factors. These investigations have suggested different mechanisms that are dependent on the nature of interaction of the abrasive solid and the surface, and also yield a plethora of possible governing parameters. In particular, there have been contradicting conclusions regarding the relationship between the compressive strength and abrasion resistance as summarised in **Table 3.**

The objective of this review is to examine published research to: (a) investigate mechanisms of concrete abrasion by waterborne solids; (b) evaluate existing laboratory test methods for concrete abrasion-erosion; (c) examine the relationship between concrete abrasion resistance and compressive strength by evaluating existing experimental test data.

The structure of the paper is such that mechanisms of concrete abrasion-erosion are first discussed together with conclusions drawn from other cementitious composites and brittle materials. Existing laboratory test methods for abrasion-erosion are then evaluated and plausible methods for relating laboratory test results to field performance recommended. Finally, approaches to modelling abrasion/erosion resistance of concrete and other brittle materials are covered and existing experimental test data used to investigate relations between abrasion-erosion and compressive strength.

RESEARCH SIGNIFICANCE

Abrasion-erosion resistance is an important requirement for concrete mixtures used in the construction and repair of concrete structures exposed to action of hard waterborne sediments. The understanding of concrete abrasion-erosion mechanisms, suitability of existing test methods and establishment of a relationship between abrasion resistance and compressive strength that accounts for abrasion mechanisms are valuable for assessment of the relative performance concrete mixtures without recourse to costly experimental campaigns. This can also be useful in the specification of abrasion resistant concrete mixtures for construction and repair of hydraulic structures, hence improving the durability of both new and repaired surfaces.

MECHANISMS OF CONCRETE ABRASION-EROSION

In order to understand the mechanisms of concrete abrasion, it is important to recognise that concrete is a brittle material. Erosion in brittle materials is mostly influenced by their composition and modes of transportation of abrasive solids. In heterogeneous brittle materials such as cement pastes which are essentially a conglomerate of small grains held together by hydraulic and chemical bonds, Bitter[7] suggests that under impact action, individual grains are dislodged in their entirety through rupture of the bonds holding them together. The resistance of these types of materials to abrasion therefore is largely determined by the strength of the inter-granular bonds rather than that of the grains themselves. This is in contrast with homogeneous materials like glass whereby the action of low velocity solids creates stress concentrations that cause cracking at a depth that is related to the size of impacting solids. At high velocities of solids however, the crack direction is determined by particle velocity[7].

In conditions whereby rolling is the dominant transport mode of the solids, Rabinowicz[8] states that material failure occurs due to a phenomenon called surface contact fatigue. This type of failure is related to general fatigue in that contacting material stresses and the number of cycles required to cause failure have a characteristic relationship[8]. Vassou et al.[9] arrived at the same conclusion after microstructural examination of concrete specimens with compressive strength ranging from 42 to 64.5 MPa (6.1 to 9.4 ksi) abraded by a rotating wheel apparatus. Petrographic examinations revealed that there were numerous cracks beneath the abraded surfaces when compared to the degree of inherent micro-cracking in concrete. This indicates that eventual spalling of surface material is attributable to the development, growth and intersection of surface and sub-surface cracks[9]. Microcracks can develop in any of the concrete phases i.e. coarse aggregate, bulk matrix and interfacial transition zone (boundary between cement paste and aggregates) depending on their relative strengths[10]. The interfacial transition zone (ITZ) is the most vulnerable phase for initiation of cracking in concrete owing to its relatively low hardness based on micro-indentation tests carried out by Sonebi[11].

Several researchers[9,12–15] attribute surface and sub-surface micro-cracking during the abrasion process of brittle materials to development of tensile and shear stresses respectively. These conclusions are based on Hertz's equations[13] for elastic contact between solid bodies. Hertz's equations show that peak tensile stresses at the surface act radially round the periphery of the contact area of the solid while shear stresses are highest at a depth of about half the radius of the contact circle[13,14]. Therefore, while contact mechanics can be applied for prediction of material fracture initiation due to the action of solids[9,14,16,17], the ensuing processes after this has occurred are not understood. The material failure process can further be complicated in concrete if hard aggregate debris plucked from the surface is present between the eroded surface and abrasive solid due to the on-set of a secondary wear mechanism called three-body abrasion[9]. Finnie[15] and Vassou et al.[9] have respectively suggested that material removal in ceramic and concrete surfaces results from the alteration in direction of crack propagation and/or interaction of cracks oriented in different directions. This can for example occur by vertical deflection of originally horizontal (parallel to the surface) cracks as well as by intersection of horizontal and vertical cracks (perpendicular to the surface)[9,17] followed by the isolated debris being plucked off the surface. Mechanisms consistent with this have also been reported in rocks subjected to impact by low-velocity solids[17]. Further, it has been established that the ratio of coarse aggregate to matrix hardness influences the mechanism of concrete abrasion[3]. In concrete mixtures where the hardness of the matrix is lower than that of coarse aggregates, the former wears out at a relatively faster rate leaving the latter protruding, and thus susceptible to plucking off the surface. However, when coarse aggregate and matrix hardness are comparable, uniform wear of the two phases is exhibited and plucking of coarse aggregates is unlikely to occur. The two scenarios are illustrated in **Figure 2.**

The strength of the ITZ, whose width typically ranges from 40 to 90 μm (1.575 to 3.543×10^{-3} in.)[11,18], influences the plucking of coarse aggregates in concretes designed with low ratios of matrix to coarse aggregate hardness.

It is thus observed that there is consensus in the explanation of abrasion failure initiation in brittle materials like glass, rock, cement pastes, ceramics etc. In concrete however, the understanding of fracture initiation and subsequent material removal processes is complicated by its multi-phase structure for which the material phase for failure initiation becomes highly probabilistic. It is also clear that concrete abrasion mechanisms influence abrasion-erosion rates. For concrete mixtures susceptible to plucking of coarse aggregates, knowledge of threshold conditions for the onset of this phenomenon are critical for reliable prediction of abrasion losses, expected to be a function of coarse aggregate (CA) grading. In fact, the maximum size of material removable in a single impact should be a function of the maximum size of CA. In contrast, abrasion loss suffered by concrete mixtures with comparable coarse aggregate and matrix hardness should not be related to CA grading.

EVOLUTION OF LABORATORY TEST METHODS

An evaluation by Liu[5] in 1980 of the rubbing, dressing wheel, ball bearing, shot-blast and rattler-type apparatus concluded that none was suitable for testing abrasion resistance of concrete exposed to sediment-laden flows. This evaluation formed the basis for the development of the underwater test[19], later standardised as ASTM C1138[20] for accelerated assessment of relative performance of different concrete mixtures. This implies that abrasion resistance indices from this test have no direct relation with concrete performance in actual field conditions. Subsequently, other test methods[21–23] have also been developed in an attempt to address perceived limitations of the ASTM C1138 test.

ASTM C1138 (Underwater) test method

The underwater test involves submersion of a disc-shaped concrete specimen of about 300 mm (11.82 in.) diameter and 100 mm (3.94 in.) thickness in water contained in a 300mm diameter steel cylinder. The sample is abraded by 70 steel balls of three different diameters (25 of 0.5 in. [13 mm], 35 of 0.75 in. [19 mm] and 10 of 1.0 in. [25 mm]). The motion of the steel balls is caused by agitation of water by an immersed paddle rotating at speed of 1200 rpm. Concrete abrasion loss is then measured at 12-hour intervals over a total duration of up to 72 hours[20] and reported as a percentage of mass of the specimen before the test. For high-strength concretes (HSC), considered as those with compressive strengths exceeding of 55 MPa (7.977 ksi)[24], sufficient abrasion may not be achieved within the standard 72 hours to be able to distinguish their relative performance. However, test durations of up to 120 hours have proven successful in the evaluation of HSC[25,26].

The reliability of any laboratory test method for investigating a physical phenomenon is greatly determined by its ability to adequately simulate the actual conditions. In the case of abrasion-erosion in the field environment, abrasive sediment transport occurs as either bedload or suspended load. The behaviour exhibited by sediments moved as the former and latter is respectively influenced by flow-induced boundary shear stress on the sediment grains[27] and flow turbulence[28]. Bed load is the proportion of the total sediment load that is in constant contact with the exposed surface and moves either by rolling, sliding or saltation[28] and is thought to be responsible for most of the wear inflicted on exposed surfaces. Some researchers[19,22,29,30] have argued that steel ball motion in the ASTM C1138 test occurs by rolling and sliding only due to the inability of the paddle agitation speed to lift steel balls off the concrete surface. This has been stated as the main limitation of this method since the impact component of wear resulting from saltation motion of steel balls may not be produced. These assertions directly contradict with similarities observed between laboratory and field abraded surfaces of both stilling basins of hydro-electric dams[19,29] and coastal defence elements[3]. **Figure 3** shows a stepped revetment armour unit abraded in field conditions at the beach in Cleveleys on the Fylde Peninsula, Lancashire, England and a concrete disc from the same mixture tested in the laboratory using the ASTM C1138 method. For laboratory damaged concrete surfaces to show similarity with those observed in field conditions where all modes of motion to occur including impact, it implies that either some degree of impact action takes place during the underwater test or it is of little significance in the abrasion-erosion of both coastal revetments and stilling basins. It is hypothesised that the similarity in abraded surfaces is because of the former. However, saltation action is not induced by paddle agitation alone; it is in combination with surface roughness which occurs after the removal of the surface matrix. Also, flow vortices generated near the rough surface contribute to the intensity of the impact action thus enabling the ASTM C1138 test method to simulate all the relevant modes of sediment transport occurring in field conditions. Despite its limitations, the ASTM C1138 test appears to be the most reliable method for assessing concrete abrasion-erosion in flows whereby sediments are mainly transported as bedload.

Other existing test methods

The suggested limitations of the ASTM C1138 test discussed have led to efforts to develop alternative test methods for concrete abrasion. The Chinese test code of hydraulic concrete[21] proposes the ring method as a robust alternative capable of simulating actual modes of sediment motion including impact action[22]. In this test, the mixture of water and abrasive solid (0.4 to 2 mm [0.0158-0.0788 in.]) at a concentration of 20% is contained in the annulus of the sample. The mixture is moved in rotary and eddying motion by an electric motor-driven agitation paddle rotating at a speed of 14 m/s (2700 rpm). This causes abrasion of vertical surfaces of the annulus which is measured at intervals of 15 minutes over a total duration of 60 minutes. The abrasion-erosion of concrete is then reported as rate of mass loss per unit area[22]. Based on the size of abrasive sediments used, the ring test appears to be most suited for the evaluation of concrete abrasion-erosion by fine sediments. Horszczaruk[23] also proposed an alternative test method that involves rotating concrete samples that are radially attached to an axle in a horizontally oriented drum containing water and natural aggregates mixture. The size of pebbles used as abrasive charge was 8-32 mm (0.315-1.261 in.) and constituted 33% (by volume) of the total mixture. The concrete samples were abraded for a total duration of 96 hours and abrasion reported as percent mass loss[23].

It is evident that all the three described test methods are similar in principle and involve agitation of water-sediment mixture to cause abrasion of concrete surfaces. Abrasion loss measurements are taken at intervals for durations of up 120 hours depending on the resistance of the concrete mixtures under evaluation. The ASTM C1138 and ring methods comprise of simple apparatus to fabricate hence suited for rapid, economical and repeatable evaluation of concrete performance whilst the rotating drum method is disadvantaged by its bulky set-up.

Among all methods covered, the underwater test has by far gained wide acceptability as the most suitable method for evaluation of concrete resistance to abrasion by waterborne solids. This is confirmed by its standardisation as ASTM C1138[20] and adoption by the Chinese test code for hydraulic concrete[21].

FIELD APPLICATION OF ASTM C1138 TEST RESULTS

There have been few research attempts to correlate ASTM C1138 findings with field performance. Horszczaruk[31] investigated the influence of the abrasive environment on the abrasion of a constant concrete mixture with a compressive strength of 127.9 MPa (18.55 ksi) and water to cementitious material ratio of 0.272 by varying the rotation speed of the agitation paddle. The concrete mixture was produced from cement type CEM 1 52.5R, silica fume, natural sand FA and basalt CA with a maximum size of 16 mm. The cement, silica fume, FA and CA contents were 450, 45, 630 and 1279 kg/m^3 (759, 76, 1062, 2156 lb/yd^3)

respectively. The study used the steel ball sizes and quantities specified in ASTM C1138[20] and concrete abrasion loss was measured at paddle rotation speeds of 350, 540, 970 and 1200 rpm. Based on the test results, a concrete abrasion loss (A_L) model was proposed as a function of paddle agitation speed (v_r) and exposure duration (t) as:

$$A_L(v_r, t) = \beta_1 v_r \ln(t+1)^{\beta_2 v_r^{\beta_3}}, \tag{1}$$

where, β_1, β_2 and β_3 are regression coefficients valid for the concrete mixture tested only. This limits the practical application of this model. Kryžanowski et al.[30] later proposed a more plausible framework for relating laboratory test results and field measurements using an energy-based approach. This entails quantification of specific of energy of steel balls in the standard underwater test and abrasive sediments in the field environment. The specific energy ratio is then used to estimate the equivalent duration of the accelerated underwater test for the exposure period in field conditions. This approach has been validated for a stilling basin with field (flow speed of 20 m/s [65.6 ft./s]) to laboratory (flow speed of 1.8 m/s [5.9 ft./s][19]) specific energy ratio of 1:10. However, the assumption that the abrasive charge is transported at the speed of water is a limitation common to models proposed by both Horszczaruk[31] and Kryžanowski et al.[30]. This is because whilst flow velocity is one of the key parameters that determine the velocity of abrasive sediments, there is a multitude of other variables that influence it such as properties of the solids, intensity of sediment collisions, surface roughness etc. Therefore, a more robust approach would be to establish the specific energy based on the actual velocity of the abrasive charge in both laboratory and field conditions. Sediment velocity in the field can be estimated from scaled models of particular applications. Nonetheless, it can be stated that progress has been made in formulating approaches for relating laboratory and field abrasion measurements. However, development of reliable models for the prediction of concrete performance in field conditions from laboratory measurements will require adequate understanding of the actual motion of the abrasive sediments rather than water flow velocities as currently proposed.

CONCRETE ABRASION RESISTANCE MODELLING

The development of a reliable model for concrete resistance to abrasion-erosion requires knowledge of its governing parameters. Whilst hardness has been successfully used to model wear resistance of metals, the composite nature of concrete in which the respective phases exhibit varying hardness levels complicates its application. Evidently, owing to lack of agreement among researchers on an abrasion resistance parameter for concrete, different but logical proposals include use of strain energy and correlations to compressive strength.

Erosion strength concept

Thiruvengadam[32] proposed the concept of erosion strength to be applicable to any material. In this approach, it is assumed that erosion of any solid surface results from the energy supplied by erosive agents and whilst a fraction of this energy is absorbed by the exposed material some is lost for instance as heat. The amount of energy absorbed by the material depends on its absorption efficiency[4]. The relationship between energy absorbed by an eroded volume of material and its erosion strength is expressed by **Equation (2).**

$$E_a = \Delta V . S_e, \qquad (2)$$

where,

E_a = energy absorbed by the eroded material;

ΔV = volume eroded material; and

S_e = erosion strength of the material.

In **Equation 2**, ΔV can be assessed by existing laboratory techniques such as the underwater test but calculation of S_e requires knowledge of the energy absorbed by the eroded material.

Thiruvengadam[32] demonstrated the application of the erosion strength concept using cavitation-erosion of metals whose erosion resistance was proportional to their strain energy. The rate of energy absorption per unit area, also referred to as the intensity of erosion (I) is obtained from **Equation (3)**.

$$I = h.\frac{S_e}{t}, \tag{3}$$

where,

t = test duration; and

h =average depth of erosion.

In the cavitation-erosion case, test results of the stated metals were used to determine the intensity of a given test device over a range of test conditions by assuming that their erosion strength is identical to strain energy. This process is essentially a calibration of the erosion test apparatus to determine its intensity. The calibrated device can then be used to assess the resistance of any material to erosion based on the rate of increase in erosion depth[32]. Although this approach has been suggested to be valid for other materials and cases of solids-impact erosion and friction wear, it has only been verified for cavitation-erosion of metals. The scarcity of experimental test data in which concrete abrasion loss is related to its strain energy makes it difficult to confirm the applicability of this concept in concrete subjected to action of waterborne solids. However, Engle[33] lends it considerable credibility for application to concrete in abrasive conditions based on theoretical analysis. This analysis proves that for brittle materials such as glass, graphite and hardened steel, impact erosion resistance (R) and strain energy estimated at their flexural strength is expressed by **Equation (4)**.

$$R \approx \frac{\sigma_b^2}{E^{0.8}} \tag{4}$$

where,

E = elastic modulus; and

σ_b =flexural strength of the material.

Similarly, Sklar and Dietrich[17] expressed erosion resistance of rock to incision by saltating sediments in river flow conditions as a function of its elastic modulus and tensile strength. This was derived by expressing the erosion resistance as energy required for abrasion of a unit volume of rock. This energy was taken to be directly and inversely proportional to the square of rock tensile strength and elastic modulus respectively. This suggests that brittle materials with high tensile strength and low elastic modulus exhibit better abrasion performance.

Compressive strength

Studies that have reported abrasion-erosion loss together with tensile strength and elastic modulus are scarce, however, empirical relations have been proposed over the years for evaluation of both tensile strength[34,35] and elastic modulus[36] of concrete from its compressive strength. A comprehensive review by Oloukun[35] showed that researchers agree that tensile strength of concrete has a power relation ranging from 0.6 to 0.8 with cylinder compressive strength. BS EN 1992[37] provides a relation for estimating elastic modulus from compressive strength only, and more recently, Noguchi et al.[36] analysed a large test dataset and concluded that elastic modulus of concrete can be more reliably predicted using compressive strength and unit weight. If these relations are considered together with **Equation (5)**, it becomes apparent that abrasion-erosion resistance (R), at least for conventional concretes, should be related to its compressive strength (f_c). Defining R as the inverse of percentage abrasion mass loss (A_L), the generic resistance model based on compressive strength can be expressed as:

$$A_L = \beta f_c^{-\alpha}. \qquad (5)$$

where, β and α are regression coefficients that can be obtained from experimental data.

Most investigations with conventional concrete mixtures undertaken with ASTM C1138 test method have often concluded that abrasion resistance improves with increase in compressive strength but concretes incorporating rubber aggregates[22,29], and those with relatively high proportions of coarse aggregates[3] do not follow this trend. In fact, concrete mixtures with rubber aggregates exhibit high abrasion resistance at increased rubber aggregate contents which are also accompanied by reductions in compressive strength. Furthermore, even for conventional concrete mixtures, abrasion-erosion resistance is not infinitely enhanced by compressive strength increase. This suggests the presence of an optimum value beyond which no significant improvements in abrasion resistance are accrued by increasing compressive strength. The range of optimum compressive strength value on abrasion resistance and the influence of concrete mixture design parameters can be examined by evaluating published ASTM C1138 test results.

EVALUATION OF EXISTING EXPERIMENTAL TEST DATA

The sources for the experimental test data analysed and critical mixture design parameters for the concretes are summarized in **Appendix A**. The data covers cube compressive strengths ranging from 23 MPa to 128 MPa (3.336 to 18.565 ksi), different water to cementitious materials ratios, aggregates types and grading. The influence of the curing regime used and age of the test specimen of 7 to 182 days are also accounted for. This represents the total set of available ASTM C1138 test data published over the last 38 years and takes into consideration the variability in concrete composition and properties that can reasonably be expected in practice. It should be noted that fibre-reinforced concretes (FRC) are out of scope of this evaluation. This is due to the fact that fibre addition can either favourably or adversely influence abrasion-erosion resistance of concrete depending on their type, size, shape quantity etc. In concrete, there is evidence that fibre addition can either reduce or increase abrasion-erosion resistance by up to 60% and 49% respectively[25,26,29,38,39] while in mortars, adverse effects on abrasion resistance of up to 87%[40] and enhancements of up to 68%[41,42] have been reported. These effects which depend on the fibre types and dosages used can significantly increase the scatter of the data points making comparative analysis difficult. Therefore, it is more rational to first establish a general formula for assessing abrasion resistance for basic concrete mixtures to which correction factors can be applied to cater for the effect of fibre addition.

It is observed that specimens for compressive strength test used by different researchers have inevitably been variable in shape and size. Concrete cylinders (150 φ /300 mm and 100φ /200 mm) and cubes (150 and 100 mm sides) have all been used in literature. These have been transformed into compressive strengths of equivalent 150 mm cubes (reference specimen) based on the relations provided in BS EN 206[43] and Neville[44]. Similarly, abrasion losses reported as either depth of damage, mass in grams, volume or in combinations were converted to per cent mass loss prior to overall analysis. Although ASTM C779-Procedure C[45] test does not adequately model abrasion action of water-borne sediments, its results have been used to qualitative comparison with those of ASTM C1138 test[20] to assess the consistency of the effects of the parameters evaluated.

Influence of compressive strength

The relationship between cube compressive strength on the 72-hour concrete abrasion loss was evaluated using ASTM C1138 test results by Liu[19], Smoak et al.[46], Nazari and Riahi[47], Rashwan and Abou-Zeid[48], Horszczaruk[25,31,49,50], Cunningham et al.[3], Wang et al.[51], Sonebi and Khayat[26], Kang et al.[22] for non-fibre reinforced concrete mixtures produced with conventional coarse aggregates (CA) of known rock types. For completeness, underwater test results in which the rock types used in the CA were insufficiently described as either natural gravel[49], crushed stone[39,52,53] or marginal[54] aggregates were also considered. In the test data where mineralogical descriptions of CA have been provided, these can generally be categorised into basalt[3,19,25,31,47,48,50], granite[19,26,48,51], limestone[19,22,26] and dolomite[48]. **Figure 4** shows the variation of 72-hour abrasion loss with compressive strength.

Figure 4 generally indicates that concrete abrasion resistance initially improves with increased compressive strength until an optimum compressive strength is attained beyond which further increase does not yield any significant abrasion resistance improvements. In fact, for the conventional concrete mixtures analysed, the optimum compressive strength for 72-hour abrasion resistance ranges from 60 to70 MPa (8.70-10.15 ksi) regardless of the concrete composition. This optimum range is important because in exposure environments where abrasion is the governing parameter in the specification of concrete, the use of ultra-high-strength concretes can be avoided thus optimising the cost of concrete. The minimum compressive strength of concrete used in abrasive conditions is normally specified in design codes based on both durability and strength requirements. The optimal compressive strength range for abrasion resistance obtained complies with the requirements of BS 6349[55] which specifies the minimum cylinder/cube strength of 40/50 MPa (5.80/7.25 ksi) for abrasive maritime conditions. All concretes currently in use in hydraulic structures, including ultra-high strength types suffer some degree of damage in abrasive conditions hence abrasion loss cannot be zero, implying that a practical predictive curve will be asymptotic to the abrasion loss (A_L) and compressive strength (f_c) axes as exhibited in **Figures 4**. This is an indication that concrete abrasion loss as a function of compressive strength can generally be represented by a simple power relation rather than complicated polynomial functions suggested by some researchers[26,50]. The equation shown in figure 4, which was obtained from regression analysis, results in a reasonable lower bound prediction for compression strengths of 60 MPa and greater. The low co-efficient of determination (24.6%) is due to the large scatter in test data observed at compressive strengths of less than 60 MPa (8.70 ksi) and is evidence of the significance of concrete mixture additives on abrasion resistance at these strengths. This equation requires improvement to account for the effect of rubber aggregates, coarse aggregate type etc. and introduction of supplementary cementitious materials (silica fume, nano-particles, fly ash and ground granulated blast-furnace slag) as examined next.

Influence rubber aggregate addition

Test results from ASTM C1138 and ring methods[22,29,30] show that concretes with rubber aggregate exhibit remarkably high abrasion resistance in spite of compressive strength reduction. The details of concrete mixtures considered can be found in the stated references. Kang et al.[22] reported 225% enhancement in 72-hour ASTM C1138 abrasion resistance at 28 days due to addition of 15% crumb rubber aggregates. This is consistent with results of Kryžanowski et al.[29,30] who also showed that replacement of sand with 9.5% fine rubber aggregates improved abrasion resistance by over 200% and 300% at 90 and 900 days of curing. The mechanisms by which rubber aggregates improve concrete abrasion resistance are not well understood but Finnie[15] notes that low elastic modulus and large Poisson's ratio of about 0.5 make rubber materials more erosion resistant. This is attributed to the reduced tensile contact stresses which minimises the risk of crack initiation and propagation[22]. However, despite the superior performance of rubberised materials in both laboratory[22,29,30] and field[29,30] test conditions, there are legitimate concerns with regards to their long-term performance, aesthetics and environmental impact[56]. Specifically, degradation by biological, chemical and ultraviolet light as well as effects of rubber particles on river and marine life are some of the areas that need further clarification.

Influence of coarse aggregate hardness

Figure 4 shows that at comparable compressive strengths, concretes produced with coarse aggregates (CA) from different rocks performed variously in the ASTM C1138 test. Concretes produced from coarse aggregates (CA) with relatively high hardness like basalt are exhibit superior abrasion resistance than those with low hardness values such as limestone[3,19,57]. This indicates that the hardness of CA used which is mainly influenced by the mineralogical composition of the parent rock is an important factor in the abrasion resistance of concrete once exposed. Although generally defined as a measure of the material's resistance to plastic deformation[8], quantitative values of hardness are in fact meaningless unless the test method used for their measurement is stated. There is no unanimity in the literature on the best test method for CA hardness for concrete used in abrasive conditions and as such, previous researchers have adopted Los Angeles (LA) abrasion[19,54], Micro Deval[3] and Mohs[19] hardness tests methods albeit with varied degrees of success. Liu[19] and Kumar and Sharma[54] concluded that there was no correlation between concrete abrasion loss measured by the underwater test method and coarse aggregate LA abrasion losses. Unfortunately, published test data on the variation of underwater abrasion loss with the Micro Deval values of CA is very limited for meaningful conclusions to be drawn. However, a strong relation has been reported between CA Mohs hardness number and underwater concrete abrasion losses[19]. Although Mohs hardness test is only qualitative in nature, empirical evidence exists showing that for minerals, it can be related to other improved hardness tests such as Vickers micro-indentation hardness[58]. According to Craig and Vaughan[59], Vickers micro-indentation hardness (VHN) of minerals has a linear/logarithmic variation with Mohs hardness scale and the relation in **Equation (6)** has been suggested by Young and Millman[60].

$$\log \mathrm{VHN} = 2.5 \log \mathrm{Mohs} + 1.00. \tag{6}$$

Vassou et al.[9] provide further evidence of potential relevance of micro-indentation hardness techniques in assessing abrasion resistance for applications where the interaction between abrasive solids and exposed surfaces is by rolling contact. Although Vassou et al.[9] focused on the characterisation of the finished surface micro-structure made up of the matrix phase, the strong correlations obtained between micro-indentation hardness and abrasion loss is also confirmation that scratch-based methods are suitable for measurement of hardness of both CA and matrix phases of concrete. This suggests that recent advances in nano-scratch methods which have proven successful in the measurement of hardness of cement pastes[61] and concrete[62] need to be exploited for evaluation of matrix and CA phases of concrete.

Other aggregate-related properties reported to influence abrasion-erosion rates in concrete include the quantity and grading of coarse aggregates. Choi and Bolander[63] observed improved abrasion resistance at high ratios of exposed coarse aggregates to total surface areas while Cunningham et al.[3] found that concrete mixtures with a high concentration of coarse aggregate experience high abrasion rates due to the poor degree of particle packing.

Influence of supplementary cementitious materials

The use of additives in the design of concrete and mortar mixtures aims to improve their properties in fresh and hardened states, and achieve environmental sustainability by using recycled waste. Concrete additives investigated for abrasion performance include: silica fume, nano-particles, fly ash, ground granulated blast-furnace slag.

Silica fume

Silica fume is the most popular additive used in the design of high-strength concretes[64] and silicon dioxide makes up about 90% of its composition[65]. ACI Committee 234[66] report provides comprehensive guidance on the use of silica fume in concrete. Test results by Kang et al.[22] at 72-hours using ASTM C1138 showed addition of silica fume to concrete at a dose of 7% of the cement content improved its abrasion resistance and compressive strength by

86% and 29% respectively. In this study however, addition of silica fume without any adjustment in cement content also resulted in 7.5% reduction in the water to binder ratio in comparison to the reference mixture. Kumar and Sharma[54] also reported abrasion resistance improvements of 14 to 16% and 26 to 40% for ordinary Portland and Portland Pozzolana cement concretes respectively after introduction silica fume at a concentration of 10% of cement content. However, maximum compressive strength increases for both cement types was only 3.2%. Other researchers[25,26,31,39,50] have also tested abrasion resistance of concretes with silica fume but have not provided reference mixtures for comparative analysis.

The results of ASTM C1138 tests are consistent with those of Ghafoori and Diawara[67,68] who investigated the effect of silica fume addition on the abrasion performance of concrete using ASTM C779-Procedure C[45]. Ghafoori and Diawara[67] used concrete specimens produced from ordinary Portland cement, natural siliceous fine aggregates and crushed limestone coarse aggregates with a constant w/binder ratio of 0.325. The optimum silica fume dosage was confirmed to be 10% of the cement content being used as a replacement for FA for both compressive strength and abrasion resistance at the ages of 7, 28 and 91 days. For the standard test age of 28 days, enhancements in compressive strength resulting from silica fume addition were 25, 64, 42 and 25% for silica fume concentrations of 5, 10, 15 and 20% respectively. At the same respective silica fume dosages and age, abrasion performance improved by 32, 49, 42 and 25%. Similar improvements in compressive strength and abrasion resistance tests using ASTM C779-Procedure C were reported by Laplante et al.[69]. Tests were carried out on a concrete mixture produced from granite and limestone CA with contents that ranged from 970 to1010 kg/m^3 (1635-1702 lb/yd^3) and FA constituted 775-785 kg/m^3 (1306-1323 lb/yd^3). Ordinary Portland cement was used in all the mixtures with water to binder (cement + silica fume) ratio maintained at 0.48. The cement content ranged from 330-350 kg/m^3 (556-590 lb/yd^3) while a single silica fume dose of 8% by volume cement. The results showed that introduction of silica fume increased compressive strength of granite and limestone aggregate concrete by 38 and 53% respectively with only marginal improvements in abrasion resistance.

Based on the limited test data available, it is evident that silica fume addition generally improves abrasion resistance of concrete. Furthermore, the optimum dosage of about 10% of cement content which is recommended for compressive strength improvement[64] is also applicable to abrasion resistance. Ghafoori and Diawara[68] attribute the reduction in abrasion resistance in concrete mixtures with excessive silica fume concentrations to the depletion of the source of calcium hydroxide in concrete which stops the excess silica fume from reacting thus becoming just filler for microscopic voids. Therefore, silica fume dosages exceeding 10% of cement content can result in reduced abrasion resistance and increased costs of concrete. Importantly, there is a considerable difference in the degree of improvement in abrasion resistance and compressive strength for a given dose of silica fume. These differences should be accounted for in compressive strength-based abrasion resistance models using correction factors.

Use of nano-particles

While the typical average size of silica fume particles range from 0.1 to 0.2 μm (4 to 8 $\times 10^{-6}$ in.)[66], the effect of nano-particles with average sizes ranging from 10 to 15 nm (4 to 6 $\times 10^{-7}$ in) on abrasion resistance of concrete have also been a subject of previous studies[47,70]. **Figure 4** shows that basalt CA concrete mixtures incorporating silicon dioxide (SiO_2) and aluminium oxide (Al_2O_3) nano-particles were superior in terms of abrasion resistance in comparison to mixtures of comparable compressive strengths without nano-particles[47]. This is consistent with results reported by Li et al.[70] and obtained from ball bearing[71] tests. In Li et al[70], the concrete mixture used was produced using ordinary Portland cement, natural sand as FA and crushed diabase CA with a particle size range of 5-25 mm. The water to cement ratio was 0.42 while the FA constituted 34% of the total volume of the concrete mixture. Titanium dioxide (1%, 3% and 5%) and silicon dioxide (1% and 3%) nano-particles were introduced as percentages of cement content (by weight). The results showed that abrasion resistance of float-finished surfaces improved by 157.0% and 100.8% with 1% and 3% silicon dioxide nano–particles additions respectively. As-struck surfaces on the other hand experienced improvements of 139.4% and 89.0% for the same nano-particle dosages. In contrast, use of titanium dioxide nano particles yield much stronger improvements of 180.7%, 147.7% and 90.4% at respective dosages of 1%, 3% and 5% for the top trowelled surface and 173.3%, 140.2% and 86.0% for as-struck surfaces. The results indicate that the optimum amount of nano-particles for abrasion resistance to be less than1% of the cement content. This improved abrasion resistance at relatively small doses of nano-particles has been attributed to the development of a more compact and homogeneous matrix phase[47].

Fly ash

Fly ash is often introduced into a concrete mixture to improve its resistance to sulphate attack, increase strength and pumpability[64]. However, its presence in concrete can also impact on it abrasion-erosion performance. ASTM C1138 abrasion-erosion test results by Horszczaruk and Brzozowski[49] showed that replacement of 20% and 30% of cement content with fly ash from a fluidized bed improved abrasion-erosion by 9% and 20% respectively at the age of 28 days whilst 10% and 44% increase was achieved at 56 days. These fly ash dosages also resulted in improved compressive strength by about 27% and 30% at 28 and 56 days respectively. However, abrasion resistance and compressive strength gains begun to be reversed when fly ash concentrations exceeded 30%. A similar study by Kumar and Sharma[54] in which fly ash replaced 40% of the cement content reported marginal increase and decrease in abrasion resistance and compressive strength respectively of concrete made from relatively hard (LA abrasion value <50%) CA. In contrast, concrete mixtures produced with relatively soft (LA abrasion value >50%) CA exhibited 18% reduction in abrasion resistance which was accompanied no change in its compressive strength at 28 days. An extensive investigation by Yen et al.[52] using Class F fly ash[72] showed that 97% of test data with fly ash dosages of 20% to 30% showed reductions in abrasion resistance that ranged from 9% to 152%. The corresponding reductions in compressive strength exhibited in 85% of the test data ranged from 1 to 31%. In concrete mixtures with 15% cement replacement with class F fly ash, it can be noted that the use of fly ash either had no effect or was beneficial (by up to 30%) in terms of abrasion resistance in 70% of the reported test data. At the same fly ash dosage, 50% of the test data exhibited increased compressive strength by up to 19%.

It can be discerned that the effect of fly ash addition on its abrasion resistance depends on the type of fly ash used, dosage as well as the properties of other concrete constituents. Concrete mixtures incorporating fly ash obtained from a fluidized bed show consistent increase in both abrasion resistance and compressive strength up to an optimum dosage of 30% above which no further performance improvements are gained. The performance of concretes produced with other types of fly ash is inconsistent but results suggest that adverse effect is apparent when fly ash replacements exceed 15% of cement content. Furthermore, the degree of effect on abrasion performance is markedly different from that of compressive strength. This can be of significance if abrasion resistance of concretes is to be fitted to a function of compressive strength.

Ground granulated blast-furnace slag

Ground granulated blast-furnace slag (ggbs) is added to a concrete mixture to improve workability, retard setting time and reduce heat of hydration as well as increase curing time in fresh concrete whilst in hardened concrete, ggbs reduces permeability, increases strength, improves resistance to sulphate attack, reduces the potential for alkali-silica reaction[73,74] and reduces chloride ion diffusivity[75]. Kumar and Sharma[54] used the ASTM C1138 test method to investigate the effect replacing 40% of ordinary Portland cement content with ggbs in two concrete mixtures produced with CA of LA abrasion values of less than and greater than 50% . The results showed that use of ggbs to together with relatively hard aggregates based on LA abrasion values improved abrasion resistance and compressive strength of concrete by 8% and 1% respectively. There was no significant effect on both abrasion performance and compressive strength for the concrete mixture produced with CA with LA abrasion value of less than 50%. Some researchers[75,76] have used other methods to test abrasion resistance of concretes with ggbs. Fernandez and Malhotra[75] used ASTM C779-Procedure C to investigate the influence of ggbs addition in dosages of 0, 25 and 50% of cement content on the abrasion resistance of concrete. The concrete mixtures were produced with water to binder ratios of 0.45, 0.55 and 0.70, binder content of 198 to 336 kg/m^3 (334-566 lb/yd^3), and had a cylinder compressive strength of 18.0-31.7 MPa (2.61-4.60 ksi) at 28 days. The CA used was crushed limestone with a maximum size of 19 mm (1103- 1175 kg/m^3 [1859-1981 lb/yd^3]) whilst natural sand was used as FA (666-759 kg/m^3 [1123-1279 lb/yd^3]). The investigation showed that the introduction of ggbs reduced abrasion resistance and compressive strength of concrete. By considering abrasion wear depths at 250 and 550 seconds of the test for specimen tested at 300 days, it is clear that abrasion resistance reduced by 6 to 55% with introduction of ggbs. The degree of abrasion resistance reduction increased with reduction in water to binder ratio. The results also show that replacement of 25% of the cement content with ggbs reduced the 28 day compressive strength by up to 8% while 50% replacement yielded compressive strength reductions of 14-18%. Comparative strength reductions were also generally observed at 91 and 365 days with only modest strength enhancement of 4 to 9% respectively being reported in concrete mixtures having water to binder ratios of 0.70.

Other materials have also been investigated for possible use in concretes exposed to abrasive conditions. A field study by Allen and Terret[2] using test coastal revetment panels showed that abrasion resistance of concrete produced with high-alumina cements (HAC) was higher than those from ordinary Portland cement and super-sulphated cements by 250% and 600% respectively. The high abrasion-erosion resistance of HAC concrete has not been fully explained but Scrivener et al.[77] suggest higher strength of the ITZ due to a combination of reduced porosity and improved mechanical interlock between the cement paste and aggregates. These are attributed to the diffusion of aluminate ions due to their relative high mobility in comparison to silica ions. Rice husk ash use in concrete to achieve environmental sustainability[78] has also been investigated using the sand-blasting method by Wada et al.[79]. However, whilst these two materials have potential use in abrasion-resistant concrete, there is currently very limited research applying these to abrasion by waterborne solids.

CONCLUSIONS AND RECOMMENDATIONS

This review focused on abrasion of concrete by waterborne solids to understand its mechanisms, evaluate the suitability of existing test methods and investigate the relationship between abrasion loss and compressive strength. The conclusions below can be drawn:

1. Besides modes of abrasive sediment transport, concrete abrasion mechanisms are influenced by the ratio of coarse aggregate to matrix hardness. Concrete mixtures with harder coarse aggregates (CA) relative to the matrix will exhibit plucking of CA and abrasion loss will be a function of its gradation. Conversely, in concrete mixtures with comparative CA and matrix hardness, CA plucking is not an important mechanism in the estimation of abrasion-

erosion loss. There is need for further research to establish threshold conditions for the initiation of CA plucking.

2. The underwater (ASTM C1138) test is the most suitable method for the evaluation of abrasion-erosion resistance of concrete exposed to coarse waterborne solids. This method adequately simulates rolling, sliding and impact wear components of abrasion-erosion and, consequently the important concrete abrasion mechanisms. This is evidenced by the similarities in surfaces of comparable concrete mixtures abraded in the ASTM C1138 test with those observed in spillways and coastal defence elements operating in field conditions. The impact wear is generated by the saltation of steel balls due to surface roughness which occurs once the matrix surface layer has been abraded.

3. Based on the limited pool of test data evaluated, the optimum cube compressive strength for concrete abrasion resistance in the ASTM C1138 test is approximately 60 MPa (8.70 ksi). Therefore, in structures where abrasion resistance governs the concrete grade specification, it would appear that no meaningful improvements in abrasion resistance are achieved by using concrete mixtures with cube compressive strengths exceeding this optimum value.

4. Abrasion-erosion loss in conventional concrete mixtures follows a power function of its compressive strength. A generic abrasion resistance model for concrete has been proposed based on compressive strength. The use of compressive strength for prediction of abrasion resistance is limited by the fact that with compressive strengths of less than 60 MPa (8.70 ksi), the influence of supplementary cementitious materials, coarse aggregate hardness, quantity and gradation becomes prominent. The existing test data is not sufficient to quantity the effects of these parameters on both abrasion-erosion resistance and compressive strength.

5. ASTM C1138 test results and field measurements can be correlated based on the concept of specific energy of the flow. However, this can only be achieved once of the specific energy

of the abrasive in the ASTM C1138 test is quantified hence the need for more research effort to be directed to this area. Further investigations are also required on the influence of concrete: exposure temperature, coarse aggregates (size, shape, texture and quantity), tensile strength and ductility on its abrasion-erosion resistance.

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TABLES AND FIGURES

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Table 1– Abrasion-erosion rates in coastal structures

Reference	Depth of Wear in mm (in.)	Exposure duration (Years)	Type of structure
Allen and Terret[2]	13to 89 (0.5-3.5)	7	Coastal revetment armour panels
Budetta et al.[80]	500 (19.7)	18	Seawall
Dornbusch[81]	1500 (59.1)	33	Seawall

Table 2– Test methods for abrasion resistance of concrete

Test method	Test code	Principle of the test	Country
Sand-blasting	ASTM C418[82]	Abrasion resistance of concrete is measured by subjecting samples to action of air-driven silica sand.	United States
Procedure A (Dressing-wheel)	ASTM C779[45]	Abrasion is induced on horizontal concrete surface by impact and sliding action of steel dressing-wheels.	United States
Procedure C (Ball-bearings)	ASTM C779[45]	Test samples are abraded by high contact stress, impact and sliding friction from ball-bearings.	United States
Bohme	DIN 52108[83]	Concrete cube samples are subjected to wear by a rotating steel grinding disc with an abrasive powder.	Germany
Underwater	ASTM C1138[20]	Concrete resistance is measured by subjecting a disc shaped sample to the action of steel balls transported by agitated water in a steel cylinder.	United States
Ring	SL 352[21]	Concrete erosion is measured by abrading sides of a concrete sample annulus with an agitated mixture of sand and water.	China

Table 3– Contradictions in the relation between abrasion loss and compressive strength

Reference	Conclusion
Liu[19]	Resistance increased with increased compressive strength
Horzsczaruk[50]	
Sonebi and Khayat[26]	
Kumar and Sharma[54]	
Causey[84]	Resistance has no relation with compressive strength
Kryžanowski[29]	Resistance increased with reduced compressive strength
Cunningham et al.[3]	Concretes with comparable compressive strengths but differing constituents exhibited varying resistance
Kang et al.[22]	Resistance increased with reduced compressive strength

Fig. 1–Severe abrasion of a reinforced concrete seawall due to action of wave-driven pebbles

Fig. 2 – Process of concrete material removal

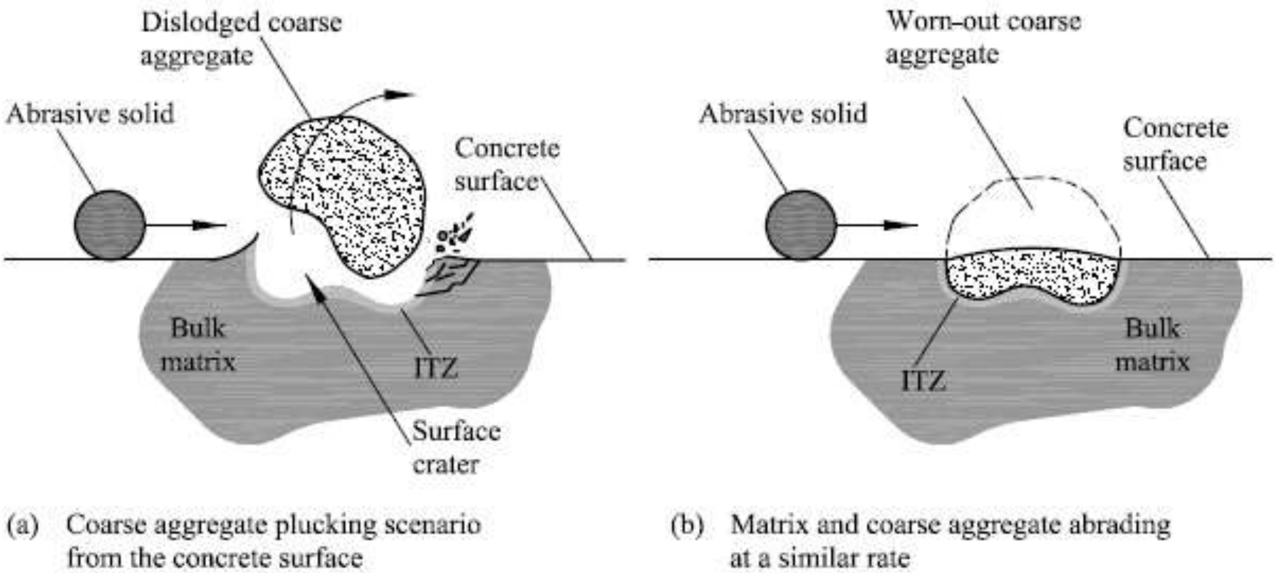
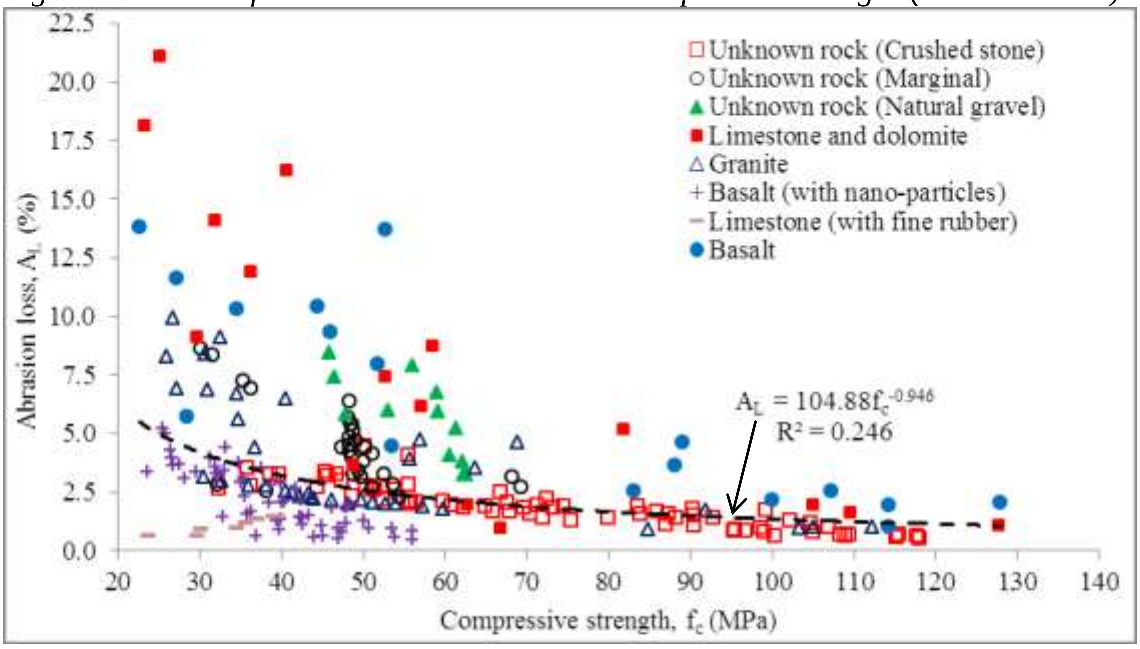


Fig. 3 – Abraded coastal revetment armour unit and laboratory sample

Fig. 4– Variation of concrete abrasion loss with compressive strength (MPa=0.145ksi)



Appendix A– Details of concrete mixtures used in the experimental data evaluated

Author Ref.	fc (MPa)	CA parameters **Key:** Rock type (1); MSA (2); Quantity (3); Ratio of CA to FA (4).	Binder description	w/b	Test scope **Key:** Age (1); Curing (2); Compression test specimen (3).
[48]	22.7-52.7	(1)=Basalt, (2)=9.5 and 19 mm (3)=620-685 kg/m^3, (4)=1.8	375 kg/m^3 OPC Type I[85]	0.35-0.55	(1)=28 days, (2)=not reported (3)=150 mm cubes
[25]	100.1	(1)=Basalt, (2)=16 mm (3)=1279 kg/m^3, (4)=1.0	450 kg/m^3 CEM I 52.5R[86] 45 kg/m^3 SF	0.30	(1)=28 days, (2)=lime water (3)=150 mm cubes
[50]	89.1-114.4	(1)=Basalt, (2)=8 mm (3)=1006 kg/m^3, (4)=1.0	470 kg/m^3 CEM I 52.5R, CEM I 42.5R & CEM III/A 42.5N[86] 47 kg/m^3 SF	0.26	(1)=28 days, (2) =water (3)=150ϕ x 300 mm
[19]	28.5-83.0	(1)=Trap rock, (2)= not stated (3)=903-1039kg/m^3, (4)=1.06-1.14	ASTM Type I[87]	0.41-0.72	(1) =28 days, (2) =water (3)=150ϕ x 300 mm
[31]		(1)=Basalt, (2)=16 mm (3)=1153-1279 kg/m^3, (4)=1.70-2.03	430-520 kg/m^3 CEM I 52.5R[86], 376 kg/m^3 CEM I 32.5R[86] 43-52 kg/m^3 SF	0.21-0.5	(1)= 28 days, (2)= water (3)=150 mm cubes
[47]	23.6-56.0	(1)=Basalt, (2)=15 mm (3)=1148 kg/m^3, (4)=2.33	450 kg/m^3 Type 1[88]; 0.5-2.0% TiO_2 and SiO_2	0.40	(1)=28 days, (2)=lime water (3)=100 mm cubes
[48]	25.9-68.9	(1)=Granite, (2)=9.5 and 19 mm (3)=620-685 kg/m^3, (4)=1.8	375 kg/m^3 OPC Type I[85]	0.35-0.55	(1)=28 days, (2)=not reported (3)=150 mm cubes
[51]	30.5-59.7	(1)=Granite, (2)=40 mm (3)=620-685 kg/m^3, (4)=2.03-2.13	OPC, Low & Moderate heat Portland cements[85].	0.40-0.50	(1)=28, 90 & 180 days, (2)= Fog room, (3)=150 mm cubes
[26]	84.9-112.3	(1)=Granite, (2)=10 mm (3)=940-1090 kg/m^3, (4)=1.42-1.47	480 kg/m^3 Type 10 & 463-498kg/m^3 Type30 cements[89], 51-55 kg/m^3 SF	0.24	(1)=28 days, (2)=lime water (3)=100φ x 200 mm
[19]	27.3-30.9	(1)=Granite, (2)=not stated (3)=1047-1067 kg/m^3, (4)=1.43	ASTM Type I[87]	0.50-0.55	(1)=28 days, (2)=lime water (3)=152φ x 304 mm
[22]	48.8-62.8	(1)=Limestone, (2)=31.5 mm (3)=1213 kg/m^3, (4)=1.86	400 kg/m^3 OPC P.O 42.5[90] 28 kg/m^3 SF	0.40	(1)=28 days, (2)=water (3)=150 mm cubes
[19]	29.7-81.9	(1)=Limestone, (2)=not stated (3)=893-1013 kg/m^3, (4)=1.05-1.14	ASTM Type I[87]	0.41-0.72	(1)=28 days, (2)=lime water (3)= 152ϕ x 304 mm
[26]	66.9-127.8	(1)=Limestone, (2)=10 mm (3)=930-1100 kg/m^3, (4) 1.43-1.49	480-490 kg/m^3 Type 10 & 475- 485 kg/m^3 Type 30 cements[89], 52-54 kg/m^3 SF	0.24	(1)=28 days, (2)=lime water (3)=100ϕ x 200 mm
[48]	23.3-58.6	(1)=Dolomite, (2)=9.5 and 19 mm (3)=1081-1201 kg/m^3, (4)=1.77	375 kg/m^3 OPC Type I[85]	0.35-0.55	(1)=28 days, (2)=Not reported (3)=150 mm cubes
[49]	45.9-62.2	(1)=Natural gravel, (2)=16 mm (3)=1028 kg/m^3, (4)=1.73	450 kg/m^3 CEM I 42.5R[86] Fly ash in percentages of 0, 20, 30, 40 and 50%.	0.40	(1)=28 & 58 days, (2)=water (3)=100 mm cubes
[3]	62.1-62.6	(1)=Gravel, (2) =20 mm (3)= 910 kg/m^3, (4)= 1.63	275 Kg/m^3CEM III[86] 155 kg/m^3 ggbs	0.38-0.39	(1)=128 & 129 days, (2)=water (3)=150 mm cubes
[54]	30.2-69.3	(1)=Marginal rock, (2)= 31.5 mm (3) =989-1270 kg/m^3, (4)=1.62-2.07	315-554 kg/m^3 OPC 43[91] & PPC[92]; 40% Fly ash[93]; 15 & 40% ggbs[94]; 10% SF[95]	0.28-0.63	(1)=28 & 90 days, (2)=water (3)=150 mm cubes
[52]	35.9-118.1	(1)=Crushed stone, (2)=19 mm (3)=743-1008 kg/m^3, (4)=0.79-2.23	275-643 kg/m^3 Type 1[85] cement; 0, 15, 20, 25 & 30% Class F Fly ash[72]	0.28-0.54	(1)=28, 91 & 182 days, (2)=air (3)=100φ x 200 mm
[39]	88.3	(1)=Crushed stone, (2)=20 mm (3)=1116kg/m^3, (4)=1.64	548 kg/m^3 OPC 53[96] 61 kg/m^3 SF	0.23	(1)=28 days, (2)=water₸ (3)=150 mm cubes₸
[53]	32.3-55.6	(1)=Crushed stone,(2)=12 mm (3)=924 kg/m^3 (4)=1.00	368-394 kg/m^3 ggbs; 79-153 kg/m^3 NaOH; 26-92 kg/m^3 Na_2SiO_2	0.40-0.50	(1)=28 days (2)=air at 23-25^{0}C Ŧ (3) 100 mm cubes

Key:
CA = course aggregates, FA = fine aggregates, f_c = compressive strength, GGBS = ground granulated blast furnace slag, MSA = Maximum size of aggregate, OPC = ordinary Portland cement, PPC = Portland Pozzolana cement, SF = silica fume, w/b = water to binder ratio.
Ŧ=Others cured in oven at 60-95^{0}C for 24 hours and then in curing room until expiry of 28 days.
₸=Not stated, hence assumed.
Conversions:
1 mm= 0.0394 inches; 1 kg/m^3=1.6856 lb/yd^3 and 1 MPa=0.145 ksi.