Briefing

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ABRASION PERFORMANCE OF CONCRETE IN COASTAL STRUCTURES

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Abstract

Abrasive wear of concrete in coastal structures can be a significant issue in areas where coarse or gravel sediments abound. In such environments, abrasion may be the governing factor for concrete specification in new construction. In the case of hard defences, concrete will constitute a major project cost thus necessitating optimisation of mix design. This briefing paper explores some of the background to the problem and existing approaches in design codes. A case study of a major coast protection scheme in the UK is discussed, focussing on the approach to concrete specification through abrasion testing.

Introduction

Structures in the inter-tidal zone are subject to mechanical degradation as a result of hydrodynamic action throughout their service life. The combination of wave and current motion with suspended sediments leads to wear of surfaces and in the case of concrete, this abrasion may exacerbate secondary means of degradation and compromise the service life of the structure. The rate of abrasion is dependent on many factors, primarily the hydrodynamic environment, sediment nature, concrete characteristics and geometry of abraded elements. For concrete elements, other degradation processes such as chemical attack may often govern design, however in locations where structures are subjected to coarse and gravel sediment transport in particular, losses due to abrasion may be highly significant.

Sediments can be classified according to the Wentworth scale in terms of particle diameters, with coarse sediments typically ranging from 0.5mm to 1mm. Gravel sediments generally consist of particle sizes in excess of 4mm and can be further divided into pebbles (4-64mm), and cobbles (64-256mm), Reeve et al (2012). In the UK, a significant amount of beaches consist of sediment which could be considered as gravel (also termed as shingle in the case of rounded pebbles), thus underlining importance of this issue to designers and managers of coastal defence structures.

As an example of the type of problems caused by motion of shingle sediments, figure 1 (left) shows how the resulting abrasive action has led to significant loss of section at a beach access stairway. Figure 1 (right) illustrates how abrasive action has reduced cover on a revetment apron causing exposure of rebar, which in turn will lead to accelerated degradation by chemical processes. Both these examples are from the same stretch of coastal defence at Anchorsholme on the north-west of England's Fylde Coast, and have occurred over a period of approximately 25 to 30 years. The abraded elements were themselves repairs to previously abraded areas, thus highlighting the significant costs and effort associated with management of abrasion damage. At the time of writing this paper, the existing defences at Anchorsholme are being replaced as part of the new £86million Anchorsholme and Rossall Coast Protection Schemes.

The work presented herein was conducted in support of the new defences at Anchorsholme and forms part of a wider investigation being conducted at the University of Manchester.

Background

Despite being a significant consideration for design and management of coastal defences, there is relatively little guidance available in the UK with regards to abrasion. This is in part due to the inherent complexity of the problem, namely the amount of variables governing the abrasion process. The UK Code of Practice for Maritime Works, BS 6349-4 (BSI, 2013), gives some general guidance on specification of concrete in abrasive environments, stating that where abrasion is expected to be significant, coarse aggregates should have at least the same hardness as the abrasive sediment. The aggregate hardness can be tested via a Los Angeles abrasion test, with a maximum allowable value of LA30 for adequate resistance. Other test approaches to derive aggregate resistance such as the micro Deval wear test are also permitted in the code. Such a prescriptive criteria may constrain the choice of aggregates used for concrete mixes and have associated cost implications. As an alternative to this, the code allows reference to historic performance of a chosen aggregate in the absence of testing.

CIRIA Report C674 (CIRIA, 2010) gives some qualitative guidance on abrasion, including potential mix designs and means of mitigation. Traditionally in abrasive environments, allowance is made for abrasion losses over the life of the concrete element by provision of a sacrificial layer of extra cover. In the case of CIRIA C674, a minimum allowance of 15mm is suggested for a 50 year design life in the most severe abrasion exposure, designated as class XM3. For certain locations such as that in figure1, this nominal provision would prove to be inadequate. Historically in the Anchorsholme region abrasion rates in excess of 10mm per year (dependent on concrete type) have been observed, Allen & Terrett (1968).

In the absence of any quantitative guidance on likely abrasion rates, designers can refer to reviews of existing concrete mix performance from historic data (where that exists) or undertaking in-situ tests. In-situ tests have drawbacks in that they are normally limited in timescale and hence may not be representative of the long-term abrasion behaviour.

Abrasion Testing of Concrete

Currently, no standard UK test for abrasion resistance under hydrodynamic actions has been codified. CIRIA C674 gives an overview of some existing methods used to assess the abrasion performance of concrete mixes. In the United States, the ASTM C1138M underwater test provides a standardised approach to hydrodynamic abrasion of concrete, ASTM (2013). The test was originally developed in the 1980s to assess the abrasion resistance of concrete intended for stilling basins, Liu (1981). In this method, 300mm diameter concrete discs are submerged in a cylindrical tank and standard abrasive charges (steel balls with a specified diameter and hardness) are rotated at a constant speed via an agitation paddle. This presents a convenient and repeatable process by which the relative performance of concretes can be determined against datum specimens with known performance in the field. Recent studies have shown that that the abrasive behaviour exhibited in the ASTM test is able to replicate qualitatively the wear patterns of concrete observed in the field, including behaviour associated with specific concrete types, Kryzanowski at el (2009, 2012).

In the case of concrete itself, there are several influencing factors which govern abrasion resistance when in contact with a given sediment type and movement. The hardness of the constituent materials, both coarse aggregate and cement matrix are important. However, the resistance may not simply be the result of material hardness, but the interplay between the constituent materials. An example of this is the case of hard aggregates in a cement matrix of lesser hardness. In this case, the matrix will wear faster than the aggregate, leading to exposure and eventual loss of aggregate via plucking action. The resulting craters left by missing coarse aggregates can provide a key for accelerated further abrasion. In this case, not only is the cement and aggregate hardness ratio important, but also the degree of bond between aggregates and matrix. Bond can be influenced by the cement type and size and shape of the aggregate, as well as the degree of particle packing.

Case Study

With a view to obtaining an optimum concrete mix design for the Anchorsholme & Rossall Coast Protection schemes, contractor Balfour Beatty working in partnership with precast specialist Macrete and the University of Manchester commissioned ASTM tests for 22 trial mixes. Mix number 1 was the datum mix which has been used in an existing coastal defence stepped revetment adjacent to the site and has exhibited a good degree of abrasion resistance over a period of 10 years in a highly abrasive environment (gravels, pebbles & cobbles). For each mix, the hardness of the coarse aggregates was measured according to the micro Deval value, a maximum aggregate size of 20mm was adopted for all mixes. For context, BS 6349 suggests a minimum micro Deval number (M_{DE}) of 10 for rock armour in highly abrasive environments defined as frequently stormy seas with shingle-structure interaction, and an M_{DE} of 30 in moderately abrasive environments. All mixes consisted of ordinary Portland cements with micro silica additions, with the exception of mixes 5 and 5A which contained a 36% replacement of ground granular blast furnace slag. Similarly all mixes contained polypropylene micro fibres at a dosage of 0.9kg/m^3, except mixes 5 & 5A from which fibres were omitted. Details of each mix are presented in Table 1.

Discussion

From the abraded surface of the datum specimen after 72 hours shown in figure 2 it can be observed that abrasion pattern is similar to that occurring in the field. Figure 3 presents the results of the abrasion tests after 12, 24, 48 and 72 hours of abrasive action. The best performing mix in relation to the datum is mix 7A which outperformed mix 1 by a factor of almost 3. This mix had the highest compressive strength in the series, however mix 9A had comparable strength yet yielded noticeably less abrasion resistance. One of the parameters separating these two mixes is the proportion of coarse aggregate (10 to 20mm) present in each mix. The degree of particle packing in the mix may be reduced by having a greater proportion of larger aggregates, which may in turn reduce abrasion resistance. Also of note is the influence of aggregate hardness, as exhibited by datum mix no.1 which had the hardest M_{DE} value, yet was outperformed by several mixes with lesser aggregates. This underscores the interplay of variables which dictate abrasion resistance.

Conclusion

Abrasion of concrete due to natural hydrodynamic action is a complex process involving many contributing variables. Standardised test methods such as one presented here, can offer a convenient way of optimising concrete mixes for design and maintenance of coastal structures. In the case study presented, the best performing mix was able to outperform the datum by some way, yet included aggregates of lesser hardness on the micro Deval scale. Based on this performance, greater flexibility for aggregate and mix design choice can be gained, resulting in associated economic benefits e.g. optimising structural section thickness.

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Mix no.	28 day cube strength f_{cu} (N/mm^2)	Water to cement ratio	Micro silica dosage (kg/m^3)	Coarse[a)] aggregate content as % of total aggregates	Coarse Aggregate M_{DE}	Age of specimen at test (days)
1	64.6	0.436	40	62	7	78
1A	67.1	0.436	40	52	8	82
1B	63.9	0.423	40	45	20	86
1C	64.8	0.423	40	35	20	90
2	64.3	0.405	40	32	20	109
2A	68.4	0.355	20[b)]	22	20	112
2B	63.1	0.423	40	27	20	117
3	65.9	0.386	40	30	20	121
3A	70.8	0.386	40	30	20	101
3B	61	0.386	40	30	20	124
4	75.6	0.382	40	28	8	88
4A	69.3	0.430	40	27	8	100
4B	74.4	0.382	40	28	8	92
5	62.1	0.382	0	38	15	129
5A	62.6	0.386	0	38	15	128
6	64.7	0.386	40	38	20	136
7	75.5	0.399	40	24	8	53
7A	89.5	0.399	40	24	8	60
8	83.6	0.382	40	28	8	114
8A	88.8	0.365	40	28	8	90
9	84	0.369	45	30	8	34
9A	84	0.369	45	30	8	88

a) Coarse aggregates defined as 10 to 20mm diameter.
b) Micro-silica alternative used (Centrilit NC)

Table 1: Test series concrete mix details

Figure 1: Abrasive wear at beach access steps (left) and sloping apron (right)

Figure 2: Abrasion pattern on 375mm tread of stepped revetment at reference site (left) and on test sample no.1 after 72 hours (right)

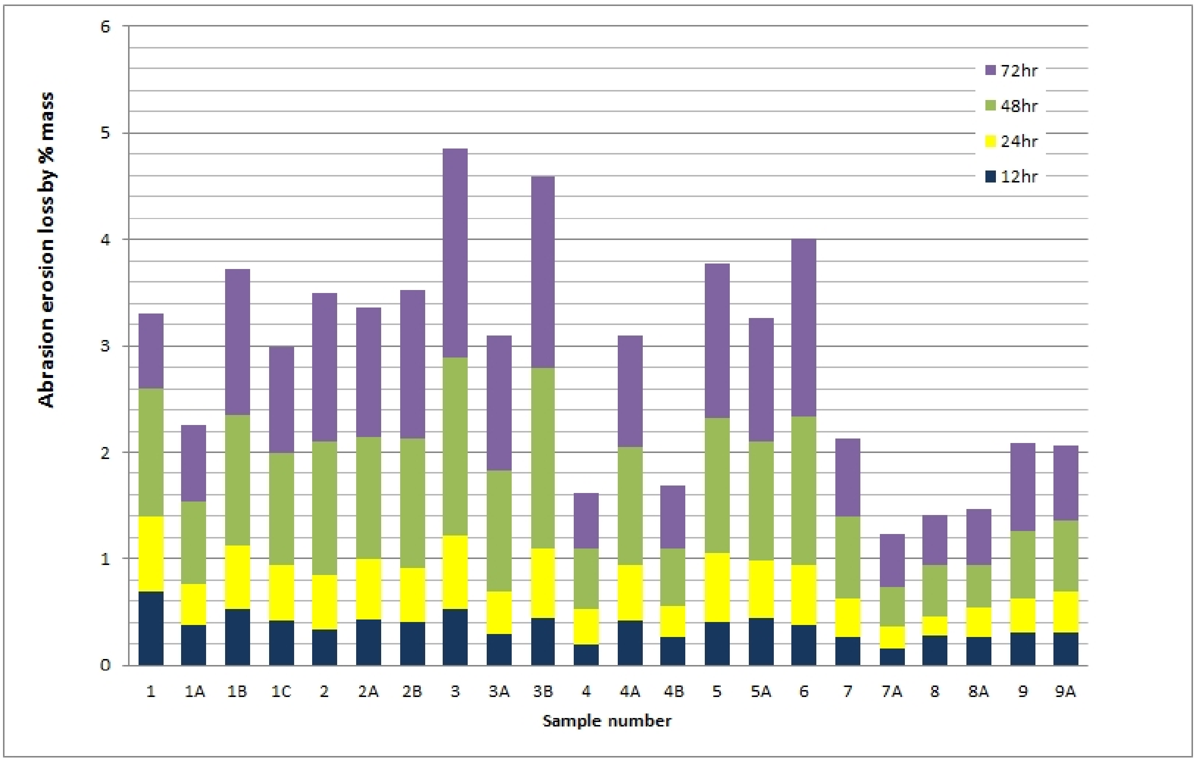

Figure 3: Abrasion loss at 12, 24, 48 & 72 hour stage