AN INVESTIGATION INTO THE USE OF SLATE WASTE AGGREGATE IN CONCRETE

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Abstract: In keeping with its approach to sustainable development, it is UK Government policy to encourage greater use of industrial waste products as an alternative to primary aggregates in concrete. This conserves natural resources and reduces the space needed for landfill disposal.

Slate has been worked in Britain for at least 400 years, providing roofing and building materials, but also generating vast quantities of waste. A recent survey in the UK showed that the overall ratio of waste production to finished products is about 10 to 1. Consequently, the volume of slate waste stockpiles are significant, between 400-500 million tonnes, with 6 million tonnes generated each year, located largely in North

Wales, but with other sources in mid Wales.

Generally, slate waste aggregates are different from natural aggregates, so that concrete made with the use of them has specific properties. Concrete normally is made from a mixture of aggregate of good quality, e.g. gravel or limestone, and cement. As aggregates generally constitute about 70 to 80% by volume of Portland cement concretes, their properties such as size, grading, shape and surface texture, have marked influence on workability, strength and durability of concrete.

This paper reports upon literature review on the suitability of using slate waste as an alternative aggregate in concrete and discuses the main constraints that hinder its uses in concrete such as, flaky particle shape, risk of alkali-silica reaction and the presence of pyrites. Recommendations to improve its efficiency are presented. Also the importance of further research into the effect of slate waste aggregates inclusion on concrete failure mechanism are suggested for future works.

Keywords: aggregate, concrete, slate, waste

1. INTRODUCTION:

The current use of resources in the construction industry is very high (CIRIA, 1999), approximately 275 million tonnes of aggregates are used each year in the UK as raw materials for construction (WRAP, 2004), of this around 65 million tonnes are sourced from recycled or secondary resources. By 2012, if UK demand for aggregates increases by an expected 1% per cent per annum, an extra 20 million tonnes of aggregates will be needed each year (WRAP, 2002). The options are to satisfy this additional demand by extracting further primary aggregates, which are non-renewable resources that cannot be replaced within typical human timescales (Sarre, 1991), or follow a more sustainable route and continue to increase the use of recycled and secondary aggregates. As both the UK and European Union moves towards more sustainable development, it is clearly desirable if recycled and secondary materials could be utilized more extensively, as substitutes, natural materials could be conserved. This has significant environmental and economic cost advantages (in terms of waste minimisation as well as sustainability benefits (Collin, 1994). Significant quantities of secondary aggregates are available both as existing stockpiles and that generated annually by industrial process. The total annual production of slate waste is estimated to be 6 million tonnes. This is added to the estimated stockpile of about 500 million tonnes (King, 1997), which puts it second only to colliery spoil in terms of the amount of waste available (Lydon, 1975).

It should be made clear that any proposal to introduce a waste materials substitute as a building material must be based on a planned appraisal of the new materials. The by-product must fulfill the engineering requirements in terms of its physical properties and must not contain excessive amounts of deleterious components, which may lead to corrosion or instability of the concrete (Gutt, 1974).

The existing knowledge of the present utilisation of slate waste aggregates in concrete shows that the use of such aggregates is limited due to three main constraints. First the flaky particles shape of slate waste fails the flakiness requirement for natural aggregates in BS 882 (CIRIA, 1999). However, the most fundamental effect of flakiness is its effect on workability and mix design, especially water demand, and therefore indirectly on the quantity of cement required to achieve any required strength grade of concrete (BRE, 1993). Second the slate waste may to some extent be reactive with alkalis from cement (Butter et al, 2000), the reaction results in the formation of a gel which absorbs water, expands, and therefore exerts internal pressure which sometimes can be far in excess of that which concrete can sustain, thereby causing the formation of micro-cracks (Marzouk, 2003). Finally, the presence of pyrite in slate waste aggregates varies. Some forms of pyrites are considered potentially expansive, if included in structural concrete mixes (Butter et al, 2000).

This paper aims to summarise the constraints on the use of slate waste as aggregates in concrete due to specifications and to make recommendations to improve the aggregate properties.

2. DEFINITIONS:

Although the terms ‘recycled’ and ‘secondary’ are often used interchangeably, it is important to distinguish between recycled and secondary aggregates production, as different operations, locations, and environmental effects may be involved (ODPM). The following definitions for recycled and secondary aggregates are widely used:

Recycled aggregates: comprise crushed, graded inorganic particles processed from materials that have been previously used in construction e.g. crushed concrete and masonry (Price, 2002). Recycled aggregates can comprise; construction and demolition wastes, asphalt road planings and used railway ballast.

Secondary aggregates: usually by-products of other industrial processes not previously used in construction. They can be further sub-divided into manufactured and natural, depending on their source. Examples of manufactured secondary aggregates are pulverized fuel ash (PFA) and metallurgical slags, while natural secondary aggregates include china clay sand and slate waste (AggRegain).

Increased environmental awareness has led to pressure to use recycled and secondary materials rather than classifying them as waste. Waste is produced when a product or material is considered by the owner to have no further use and is discarded, although it could be viewed as a 'resource' in the wrong place, waiting to be used (Price, 2002).

3. HISTORICAL BACKGROUND

The history of the use of slate in construction buildings is known to go back nearly two thousand years. The Romans used it in building their fort of Segontium, near Caernarvon in North Wales (Lindsay, 1974); they clearly appreciated its versatility and used it for roofing and flooring and even as a lining material for the channel of the hypocaust.

North Wales has always been by far the largest producing area of slate although it is quarried in Mid-Wales, Cornwall, Devon, Cumbria and the Highlands of Scotland (Sherwood, 1995). Slate quarrying reached its peak in the 19th century when the development of the canal and then rail networks meant that slates could be transported cheaply from the slate-producing areas to all parts of the country for use as roofing material. From the turn of the century slate quarrying fell into rapid decline as tiles once again became the cheapest method of roofing. During the last ten years there has been an increase in production but this is still at a very low level compared with Victorian times (Sherwood, 1994).

The geological origins of slate from argillaceous sedimentary deposits, or sometimes from volcanic ashes that have been metamorphosed have give a rock that exhibits characteristic 'slatey' cleavage (Crockett, 1975). However, only the rock suitable for splitting is acceptable because the main end use is for roofing. This factor together with the losses incurred during cutting and splitting of large blocks of good slate leads to high proportion of waste at all stage; nearly 90 per cent of the quarried output accumulates in mountains of loose tipped waste such as those at Blaenau Ffestiniog (Gutt, 1974).

4. CHARACTERISATION OF SLATE WASTE:

Slate is a metamorphosed mudstone with well-developed cleavage and parallel alignment of mineral constituents (DoE, 1991). The most important constituents of slates are shown in Table 1. Illite may also be present, together with minerals such as calcite, dolomite, pyrite, feldspar, graphite and other carbonaceous matter, as well as small quantities of other minerals (Crockett, 1975).

Table 1: The most important mineral constituents of slate (Watson, 1980)

	% by weight
Sericite mica	38-40
Quartz	31-45
Chlorite	6-18
Haematite	3-6
Rutile	1-1.5

The characteristics of different slates depend on the nature of the original sediments and the modification of their mineralogical constituents, as well as the formation of new ones, during metamorphism (Watson, 1980). Mill waste, mainly the ends of slate blocks and the chippings from the dressing of the slate, consists mainly of slate itself, but rocks such as cherts which are sometimes interbedded with the slate and igneous rocks may also be found in it (Sherwood, 1994).

Although most common slates are derived from argillaceous sediments, there are some which have been formed from accumulations of fine-grained volcanic ash and dust (Watson, 1980).

Chemical Composition:

A typical chemical analysis of slate waste from different quarries is given in Table 2. The waste is chemically inert (Sherwood, 1995) and the principle minerals that it contains are relatively stable. However, some examples can contain significant quantities of calcite and pyrite which are both subject to attack, particularly in industrial areas (Watson, 1980); also it is possible that the slate waste contains quantities of finely divided silica and mica which will to some extent be reactive with alkalis from cement (Butter et al, 2000). This possibility is being discussed as part of this study.

Table 2: A typical chemical analysis of slate waste from different quarries (Crockett, 1975; Charmbury, 2004; Gutt, 1974)

	(Crockett, 1975)	**(Charmbury, 2004)**		**(Gutt, 1974)**
	Typical	**Penrhyn**	**Ffestiniog**	**Scottish quarries**
	% by weight			
SiO_2	45-65	58.38	54.10	54.7
Al_2O_3	11-25	19.58	22.29	18.1
FeO	0.5-7	-	-	5.4
Na_2O	1-4	0.12	0.78	1.5
K_2O	1-6	0.35	4.20	2.8
MgO	2-7	2.43	1.54	3.9
TiO_2	1-2	0.68	1.11	1.0
Fe_2O_3	-	11.27	9.91	1.7
Mn_2O_3	-	-	-	0.1
MnO	-	0.21	0.35	-
CaO	-	1.52	0.45	1.7
SO_3	-	<0.01	0.10	0.4
CO2	-	0.50	-	-
F	-	-	-	0.02
P_2O_5	-	-	-	0.15
Sulphide S (other than pyretic)	-	-	-	0.13
Pyritic and Organic	-	-	-	0.4
Loss on ignition	-	3.77	4.95	6.7
Not determined	-	1.19	0.22	1.3

Physical Properties:

The properties of different slates vary rather widely depending on their source. Perhaps one of the most significant properties of slate is its cleavage. The way in which slate has been formed generally gives it low porosity this means that many slates are highly resistant to weathering (Watson, 1980).

A summary of the physical properties of Welsh slate waste is given in Table 3 (Sherwood, 1994). The waste materials from slate production comprise various sized fragments (Dhir et al,1996). The slate waste, provided that it can be crushed to satisfy the relevant grading requirements will satisfy most other requirements with regards to factors such as plasticity, particle strength and durability (Sherwood, 1994).

Table 3: A summary of the physical properties of Welsh slate waste (Sherwood, 1994)

	Source*					
	A	B	C	D	E	F
Property						
Water Absorption(%)	0.2	0.3	0.3	0.3	0.2	0.3
Flakiness Index	93	100	100	100	93	98
Elongation Index	23	29	34	34	23	27
Aggregate Crushing Value (kN)	25	29	26	30	24	23
Ten Percent Fines Value (dry) (kN)	160	130	140	120	170	160
Ten Percent Fines Value (soaked) (kN)	110	90	80	70	110	100
Aggregate Impact Value	27	29	29	33	28	28
Relative Densities:						
Oven-dry	2.80	2.76	2.75	2.80	2.80	2.80
Saturated Surface Dry	2.82	2.78	2.77	2.82	2.82	2.81
Apparent	2.84	2.80	2.79	2.84	2.84	2.83
$MgSO_4$ Soundness	99	98	98	98	99	98
Plasticity Index	0	0	0	0	0	0
Slake Durability Index (%)	96	94	95	94	96	96
Sulphate content ($g.SO_3$/litre)	0.01	0.01	0.01	0.01	0.01	0.01

*Sources of slate waste aggregate:
A-Penrhyn B- Ffestiniog C-Llechwedd
D-Croes-Y-Ddu-Afon E- Aberllefni F- Burlington

5. USES IN CONCRETE:

The literature contains references to various possibilities of using slate in concrete. It can be used as a concrete admixture from slate powders, as a dense aggregate from crushed slate and as a lightweight aggregate from expanded slate, the latter being beyond the scope of this study.

1. Slate powder as a concrete admixture:

Slate powder has been considered as a partial replacement for cement in conventional concrete (Watson, 1980). In 1976, Watson et al determined the compressive strength of concrete specimens in which fine slate powder had been blended with ordinary Portland cement using 0, 10 and 20% slate in dry mix. They concluded that the slate powder does seem to be primarily that of an inert filler. Also, there is a possibility of cost reduction, and perhaps increased workability. On the other hand in 2000, Butter et al found that the addition of slate dust reduced the cost of concrete made with alternative aggregates, which in general demanded relatively high cement contents to obtain the workability and compaction required for good quality concrete.

2. Crushed slate as dense aggregate in concrete:

A number of publications have referred to the possibility of using slate as a dense aggregate in concrete.
In 1966, McGhee et al pointed out that the platey and often elongated shape associated with the slate particles is considered to be unconducive to good workability and may have an adverse effect upon strength and durability. They concluded that production of workable mixes could be made to produce concrete conforming to specifications and the materials appeared to provide adequate compressive strength, good flexural strength and excellent freeze-thaw resistance. Their work has suggested that some other properties, including aspects of durability and long-term behavior, appear to be satisfactory for the particular slate that they investigated.

Another investigation was carried out in connection with the construction of a haul road in North Wales. The slate was crushed to a grading similar to one given in a United Kingdom specification for cement-bound granular material for sub-base and road base construction. The flakey, elongated nature of the slate particles led to the addition of sand to achieve reasonable compaction and a selected pulverized fuel ash (PFA) was used as a pozzolan, which increased the volume of cementitious paste. The initial work anticipated that the aggregate was randomly oriented and the finish obtained on the test cubes was found to be very good when PFA was added (Watson, 1980).

The case of a dam in southwest England in which the slate waste was used in conjunction with china clay sand as an aggregate for concrete is quoted in BS 6543, section 18.4. To obtain some workability the aggregate to cement ratio was reduced and a plasticiser was used. Building Research Establishment (BRE) visited this dam recently and the concrete was found to be in excellent condition.

After visiting sixteen slate quarries in 2000, Butter et al pointed out that the variability of the slate was greater than had been anticipated. The quality of material varied from good to poor rock hardness and in the quantity of pyrites present. It has been demonstrated that slate waste from some sources can be processed to create an aggregate which, in carefully designed mixes, will produce concrete with strengths comparable to normal aggregates. Nevertheless, it was found that there was a risk of alkali-silica reaction in the presence of high quantities of alkali in mortar samples.

6. CONSTRAINTS TO WIDER USES:

Although slate waste can be used as an aggregate in concrete, its use is limited due to three main constraints:

Particle shape

The relation between concrete composition and its mechanical properties has long been a matter of research interest (Ozturan et al, 1997; Davis et al, 1989; Davis et al, 1992). Aggregates generally constitute about 70 to 80% by volume of Portland cement concretes (Mindess et al, 1981). Due to the large volume fraction it occupies in concrete, aggregates exert a major influence on volume stability and durability. The properties such as size, grading, shape and surface texture have marked influence on workability and strength of concrete. The flaky nature and the smooth surface texture of slate particles (Mears, 1975) may cause problems in workability and strength of concrete. First, aggregates having more angularity contain more voids than rounded ones and hence demand more water to produce workable concrete. This will have an indirect effect on the quantity of cement required to achieve any required strength grade of concrete (Shergold, 1953; Kaplan, 1958; Murdock, 1960). Secondly, aggregate surface texture is one of the most important factors affecting bond strength; rough surfaces usually have a higher bond than smooth surfaces (Kaplan, 1959).

Slate waste aggregate fails the flakiness requirement in BS 882 (CIRIA, 1999), which requires the value not exceeding 50 for uncrushed rock and not exceeding 40 for crushed rock or crushed gravel. The flakiness index is the percentage of flaky particles in aggregates retained on the 6.3 mm and larger sieves, and is tested according to BS 812:Section 105. The flaky shape of slate waste can exclude its general use in concrete apart from specially designed mixes (CIRIA, 1999).

Constraints surrounding flakiness can, however, be overcome. In 2000, Butter et al utilized a crushing process to improve the shape of the slate to make it acceptable in concrete mixes. The results were promising; the shape of the aggregate improved, and this was verified by the reduction in the flakiness index. The same process was used by Mears: grid rollers, which break the longer needle-shaped pieces of slate into small pieces, were used to overcome the problems in compaction. On the other hand, in the example of haul road in North Wales (Watson, 1980), it was found that the addition of sand and a selected pulverized fuel ash (PFA) led to the achievement of better compaction. While other researchers concluded that using extra cement with a plasticizer (BS: 6543, 1985) or the partial replacement of Portland cement by slate powder (Watson et al, 1976) were necessary to increase workability.

Alkali-silica reaction

Aggregates for concrete should be sufficiently hard and strong for the grade of concrete required, should not react adversely with the cement nor contain impurities that do so and should remain reasonably stable when subjected to change in moisture content (BS 6543, 1985). There is a risk of alkali-silica reaction (ASR) in the presence of high quantities of alkali in mortar sample (Butter et al, 2000), as the slate waste aggregate may contain quantities of finely divided silica and mica. The reaction is known to cause cracking and expansion of concrete structures (TR. 22). ASR is an internal chemical reaction between alkaline components in the cement and certain active mineral constituents in some aggregates. The alkaline components, such as sodium and potassium that are derived from cement, as well as other constituents, cause the dissolution of the siliceous components of the aggregate resulting in the formation of a non-deforming gel. As the gel continues to absorb moisture, the micro-cracks widen (Marzouk, 2003). On the surface, the cracks appear in the form of map work cracking. Extensive research on field structures has indicated that crack widths can range from 0.1 to 10 mm in extreme cases (Neville, 1995; Swamy, 1994).

BS 8110:part 1:1997 defines some requirements for ASR but the main source document is Concrete Society Technical Report Number 30. The most frequent method of specification relates to the limitation or immobilization of alkali, but occasionally non-reactive aggregate combinations are required and these may be assessed by the concrete prism test according to BS 812-123:1999 or petrographic examination. In the UK the most common method for minimizing the risk of cracking due to ASR is to specify a maximum alkali cement of 3kg/m3 for the concrete. This figure includes alkalis from the Portland cement and from other sources. Additionally, where PFA and ground granulated blast furnace (GGBS) is being used, it has been recommended that the effective alkali content of these materials be taken to be one-sixth and one-half respectively of their total alkali contents (TR. 22).

A number of approaches to avoid the deteriorative effects of use of alkali-reactive aggregate were proposed by many researchers. In 2004, Mather revealed that many aggregates that have some degree of reactivity will be innocuous when used with low-alkali cement. If an alkali-silica reactive aggregate must be used with cement that is not low-alkali, damage can be avoided or minimized by using adequate amounts of a suitable pozzolan or slag. Additionally, in 2000, Butter et al demonstrated that the presence of PFA would lower the risk of ASR. It was further found that the use of slate dust, produced during the crushing of the aggregate, as a partial cement replacement, was able to minimize the risk of the reaction while, in 2003, Alexander recommended that 50% replacement of cement with corex slag was specified to prevent ASR damage.

3. Presence of pyrite

From the research results so far, it is clear that the presence of pyrite should not itself be a cause for the rejection of an aggregate and not all forms of pyrite are unstable. Minor amounts of pyrite do not generally cause any serious problems though they can lead to surface staining of the concrete. However, a fuller investigation will be necessary if the amount of pyrite in the aggregate is large or especially if it occurs as finely disseminated material in cleavage planes. Such form of pyrite can oxidize causing expansion and a number of adverse consequential effects, including sulphate and acid attack on the cement matrix of the concrete (DoE, 1991).

7. CONCLUSIONS

To sum up, there have been instances in which slate has actually been used as the dense aggregate in concrete. It was generally found that these aggregates have high resistant to weathering and low porosity. The principle minerals that it contains are relatively stable and inert. Additionally, it has been shown that concrete of about 30 MN/m2 compressive strength at 28-days can be produced from mixes that have adequate workability characteristics for practical use.

Although the use of slate waste aggregate in concrete is limited due to many constraints, with careful mix design it can still be used. The experimental investigations show that the workability of slate waste aggregate concrete may be significantly improved by using a crushing process to improve the shape of the slate particles. Also, using extra cement with a plasticizer or using slate powder as a partial replacement to Portland cement can increase workability. On the other hand, in order to minimise the risk of ASR, low-alkali cement should be used. If cement that is not low-alkali must be used, it has been found that the presence of PFA or the use of slate dust or the use of corex slag were able to minimise the risk of the reaction.

Generally, lack of widespread reliable data on aggregate substitutes can hinder its use. To design consistent, durable slate waste aggregate concrete, more testing is required to account for variations in the aggregate properties. Concrete is a composite, and its properties depend on the properties of its component and the interaction among them. In the composite many characteristics of the aggregate affect properties in fresh concrete, which later will modify the behavior of hardened concrete. The shape and texture of the coarse aggregates change the workability, inducing differences in consolidation; similarly, any difference in fluidity of the matrix will result in a significant change in bond strength. As a result, the analysis of the effect of any particular characteristic of the aggregate in concrete is more complex as aspects of fresh or hardened concrete are superposed, making it difficult to compare the effect of an isolated variable given the superposition with others.

There is general agreement about the importance of the matrix-aggregate bond. It is known that the transition zones (interfaces) are the weakest link of the composite material, playing a very important role in the process of concrete failure, as crack growth usually starts at the matrix-aggregate interfaces. The critical interfaces are generally those between coarse aggregate and mortar. Crack propagation usually starts at the interfaces, and the cracks grow through the matrix. Coarse aggregates arrest crack growth, producing meandering and branching of cracks and some particles are fractured. This mechanism depends greatly on the characteristics of the aggregates, especially surface texture and shape, and on the strength differences between aggregates and matrix. Thus the type of coarse aggregate is one of the most important variables affecting the behavior of concrete.

In light of the above, a concrete mixes made of slate waste aggregate will be produced taking into consideration the existing knowledge to overcome those problems associated with workability and ASR. The effect of slate waste aggregates inclusion on concrete failure mechanism, including tensile and compressive strength, stiffness, energy of fracture and crack pattern will be tested. A comparison between these results and the results from natural aggregate mixes will be made.

Finally, The composition of slates from different sources varies considerably and some contain minerals, for example pyrite among others, which can cause problems in concrete. As a result of this, it is most important to note that, before any particular source of slate waste is actually used for producing concrete, a proper evaluation must be carried out to ensure that the particular material in question has no detrimental effect upon any aspect of the performance of the concrete under service conditions.

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