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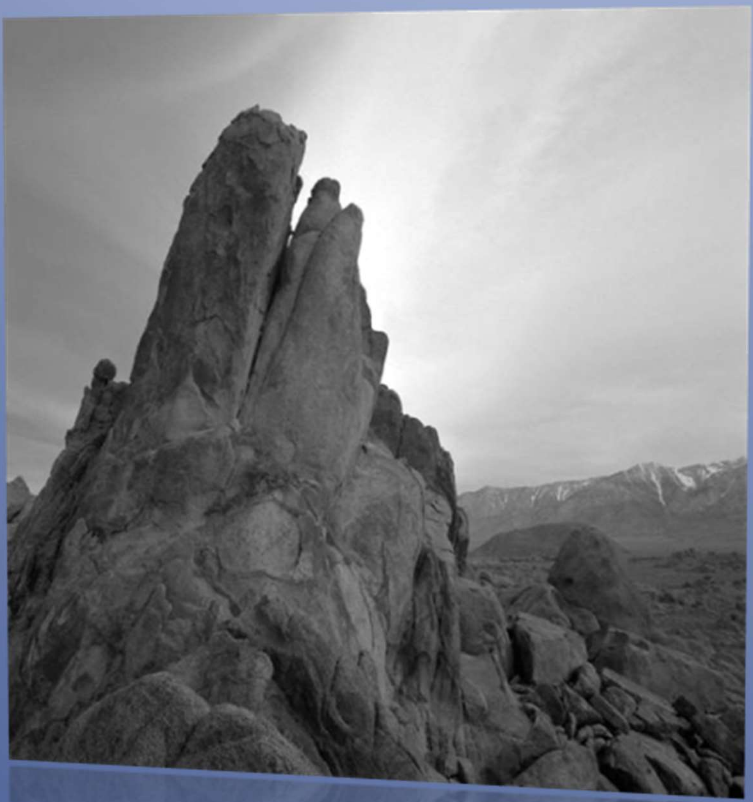

Physical and Chemical Properties of the Slate Aggregate

Dr Petar Radanliev – University of Oxford, Engineering Sciences Department.
petar.radanliev@oec.ox.ac.uk

By-product aggregate materials - This paper examines the physical and chemical properties of the Welsh slate aggregate in order to establish whether Cambrian and Ordovician slate waste from North Wales can be a viable aggregate material.

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Abstract

The slate aggregate has long been perceived as a substandard, low quality waste material with its physical and chemical properties not being competitive with those of the primary aggregates. It is assumed that the slate aggregate particles are not strong, that is not durable and will not compact. This research aims to address those claims and review the available literature on the performance of the slate aggregate. The review inaugurates by analysing the physical, chemical and mechanical properties of slate, before expanding into a literature review of laboratory testing's on the effect of moisture content on density, compaction and layer thickness of slate aggregate.

The paper reviews case studies of construction projects in North Wales, where the slate aggregate has been used for general fill and road building for many years. Some of the case studies include the A55 coastal road and duelling of the A5 in Anglesey (WRAP, 2004), where slate aggregate was successfully used as sub-base. The paper also investigates why many civil engineers are reluctant to use the slate aggregate and regard the material as sub-standard, flaky aggregate. The research paper reviews the potential usages and various products the slate aggregate is suitable for and satisfies the requested standards.

The final topic reviewed is the cost of transporting slate aggregate compared with the cost of transport for primary aggregate and the introduction of the Primary Aggregates Tax (Parliament of the United Kingdom, 2011). The last topic includes a critical analyses of the claims that the slate aggregate a commercially viable construction material despite its remote location (Woodward et al, 2004). The transportation cost and the supply chain complexities must be evaluated prior to considering the long-term sustainability of the product (Radanliev *et al*[1-6], 2014, 2015, 2016).

Keywords: North Wales; slate mining industry; slate aggregate; secondary aggregate; transportation cost; low quality waste material; physical and chemical properties

1. Physical and Chemical Properties of the Slate Aggregate

Slate Aggregate is a mineralogical combination of mostly quartz, illite and phyllosilicates, with lesser quantities of other minerals such as iron oxides and sulphides(Campos et al et al., 2004). More precisely, slate is a fine-grained metamorphic rock originating from mudstones and siltstones. XRF analysis gives its composition to be about 60% silica, 20% alumina and 8% iron, with minor amounts of MgO (3%), Na2O (2%) and K20 (3%) (Woodward et al, 2004). The process of slate creation starts when shale is placed in direct pressure caused by movement of Tectonic plates in the earth's crust in combination, with the continuous pressure the temperature inside increases and causing a high heat temperature in the rock (GSU, 2000, Fieldhouse, 2006). The initial new mineral created under this process has a planar texture named foliation (Fichter, 2000), depending on the pressure and temperature this initial mineral is subjected to it can be transformed into a slate (Fieldhouse, 2006). Through this process the slate gets its exceptional rock cleavage, layered structure and uniform flat planes. Thanks to these specifications slate is being used for many purposes, such as roof and floor tiles with life expectancies of over 200 years, nonporous good insulation properties and resistance to acid and pollutants (Fieldhouse, 2006).

This research paper performed a literature review of current and historic studies on the different types and the performance of Welsh Slate Secondary Aggregate (Radanliev, 2014, Radanliev 2015). According to Sallery (2005) the metamorphic rock in Wales is present since the Paleozoic age between 350 and 500 million years ago (Sallery, 2005). Fieldhouse (2006) stated that there are three forms of slate in Wales which are Silurian, Ordovician and Cambrian (Figure 1-1).

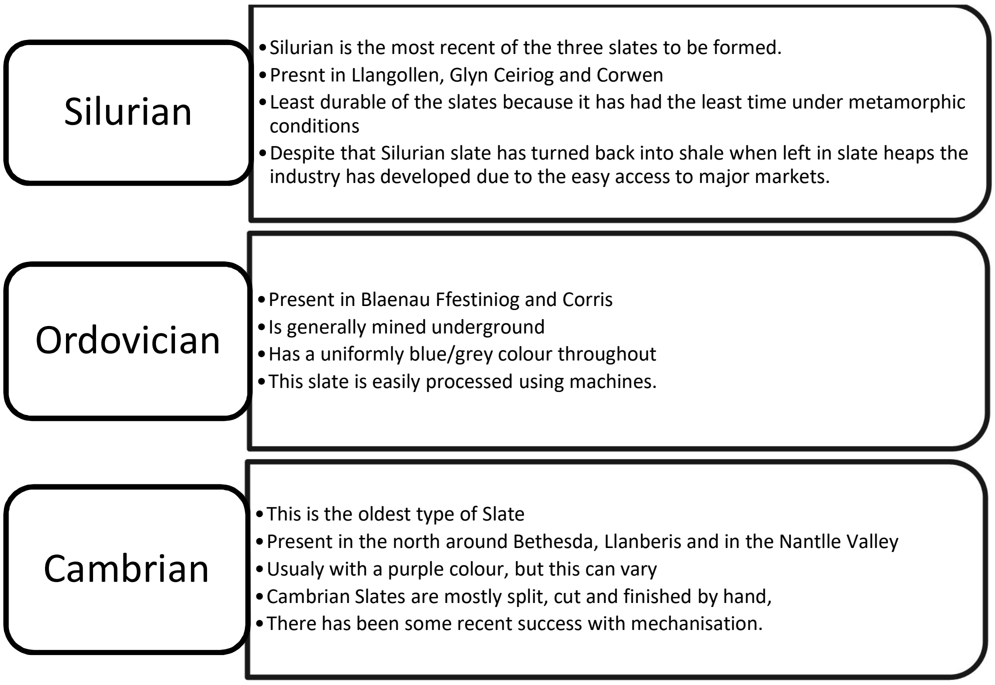

Figure 1-1: Silurian, Ordovician and Cambrian slate aggregate

The literature review discovered that different studies applied a range of testing methods to get reliable results of the Welsh Slate Aggregate physical and chemical characteristics and performance. The most detailed study identified used regime using gyratory and Marshal compaction to investigate the Welsh Slate Aggregate performance (Woodward et al, 2004). This study has proven that there are predictable interactions between moisture content, grading and density in the slate aggregate and that slate was not particularly difficult to compact. Prior to Woodward et al (2004) study, it was reported that the slate has a high relative density, even higher than for most primary aggregates (Goulden, 1992). Goulden (1992) tested and found the fraction passing 425 μm sieve to be non-plastic and the sulphate content very low in slate aggregate, adding to this a very high flakiness index was measured in this report of, 93, and a high elongation index of 23. Dawson and Nunes (1993) reported that the horizontal permeability of the slate aggregate can be expected to be much higher than its vertical permeability, and that to be non-frost vulnerable the proportion passing 75 μm has to be less than 9% (Dawson et al, 1993). To be more precise, the slate aggregate is of laminar (anisotropic) nature compared to other traditional cubic (isotropic) aggregates.

Being from a reliable, regular source, relatively inactive but durable means the slate aggregate can be used and perform well in many different contexts. However, when slate travels out of North Wales it is being used by engineers with relatively little past experience of the aggregate. When tested using conventional methods such as Clegg, the impact may give a different impression of its compaction compared to a more conventional type of aggregate. To present this argument, this paper reviewed literature on studies conducted to analyse and compare date on how the performance of slate aggregate may be predicted and detailed an investigation of results from using standard and non-standard testing on slate aggregate.

2. Description of the Slate Aggregate

The demand for aggregates in the construction industry, the road construction and re-construction industry has been increasing and is likely to continue to increase (Dawson et al, 1993). It is also becoming more and more difficult to obtain new planning consents for extraction of primary aggregates due to the environmental impact, the public concern and the difficulty of obtaining sites for new quarries (Dawson et al, 1993). Regardless of the amount of consultation, any plan for new quarrying sites attract strong opposition (Jackson, 2010). In the same time large quantities of slate waste are stockpiled around the UK and more waste aggregate is arising from the slate extraction industries.

The British Department of Transport (DoT) and Department of the Environment (DoE) have identified methods to stimulate the utilisation of secondary aggregates to: 'reduce the demand for primary aggregates, allowing the preservation of finite resources; while reducing the environmental costs associated with conventional aggregate quarrying on the one hand, and waste dumping on the other hand; allow commercial benefit from the use of waste materials since they are already financed by other industrial processes which generate them and, if not sold, have to be stored thereby incurring in extra costs' (Dawson et al, 1993).

Slate Aggregate is literally quarried waste aggregate; but the physical characteristics of the slate aggregate are meeting the requirement of the department of transport specification for highway works, clause 803. Similar specifications can also be identified in other hard inert materials, slag or rocks, such as Limestone, or Granite. However, the slate aggregate is responsible for one of the largest volumes of dumped aggregate in the UK (Dawson et al, 1993).

A range of aggregate types used to provide structural support below roads can also be used for providing structural support for buildings. The degree of control over contaminants, and the grading of the aggregate, is dependent on the sub-base type and the loads it is expected to bear during its lifetime.

3. Predicting the Performance of Slate Aggregate

Despite the fact that the slate aggregate meets all the Department of Transport specifications (DfT, 2010) and that can be processed by selection and crushing into Type 1 and Type 2 sub-base (WRAP, 2009, DfT, 2010) and that all the testing's from various laboratories presented good resilient modulus characteristics (Celtest, 2006), its present utilisation is very limited (Dawson et al, 1993). The main usage so far has been pipe bedding, drainage material, embankment fill, capping layers and only over the past ten years, as Type 1 aggregate for unbound granular sub-bases (Dawson et al, 1993).

Ever since 1941, it has been documented that one possible use for slate aggregate is to produce expanded lightweight aggregate for use in concretes (Conley, 1942). The process of producing lightweight slate aggregate involves heating slate aggregate to around 1200^{o}C, at this temperature gasses are produced and trapped in the mineral producing honeycomb structure within the mineral, creating a strong lightweight aggregate (Holm, 1993). There are a number of methods for producing lightweight aggregates based on the method mentioned above, some of the methods as stated in Fieldhouse (2006) are:

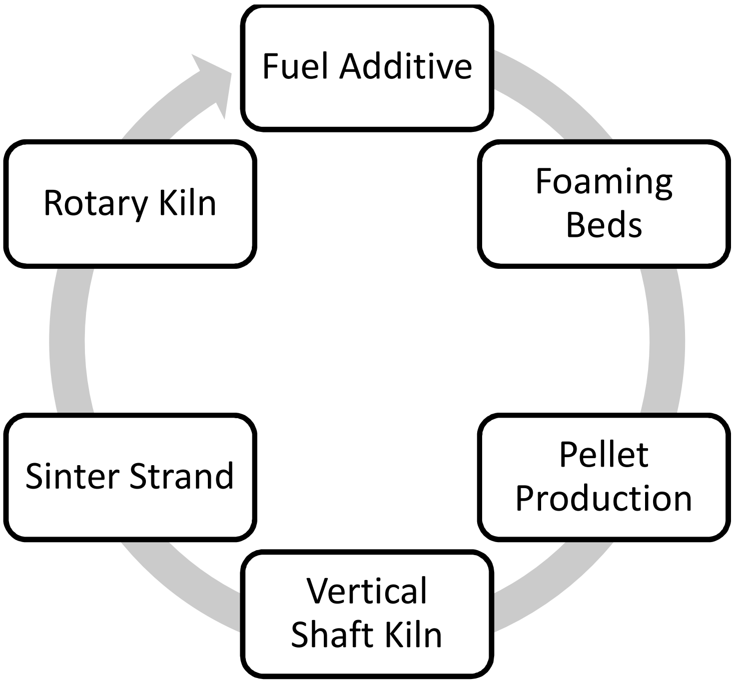

Figure 3-1: Methods for producing lightweight aggregates

The testing's in Conley (1941) study showed that by using the expanded slate in concretes, the civil engineers are not only getting a strong aggregate for specific uses, but also the advantage of lightness which can be used in structures such as walls and roofs of buildings, suspension-bridge roadways and a number other usages where weight is an important factor (Conley, 1942). Furthermore, lightweight aggregates concrete blocks are ideal for structural buildings as they have good fire resistance properties (Dhir, 1996, Lindgard and Hammer, 1998) apart from reporting that expanded slate lightweight aggregates products are fire resistant, they also documented that slates have no combustible content and are chemically inert. Another advantage of expanded Slate Aggregate is the fact that because of the reduction in dead load slate lightweight aggregates have a comparable strength with normal or heavy weight aggregates (Fieldhouse, 2006). Lightweight aggregates are used widely in the industrial and commercial sectors, Stanley (2002) listed various usages for lightweight aggregates (Appendix A). Imaginably, these uses could attract a number of customers and consume an appreciable annual tonnage of slate aggregate from Blaenau Ffestiniog.

The latter study of Woodward et al (2004) research established that slate aggregate fulfils the physical characteristic property requirements specified for unbound use in the UK road construction and that it is suitable for use in asphalt layers. While Sherwood (1994) study found that slate aggregate is a material with a high potential for usage in pavement foundation as Unbound Capping Layer and Unbound Sub-Base, and that the slate aggregate has some potential to be used as a Cement-Bound material (Sherwood, 1994). The highest quality slate aggregate contribute to improvements in stiffness of asphalt road-base compared with more commonly used aggregates (QPA, 2011). Mansur et al (2005) found that slate powder aggregate have a potential use in the manufacturing of ceramic pieces by applying the slip casting process (Mansur, 2006). While Campos et al (2004) in their study documented that recovered slate aggregate is a suitable material for use in ceramic tiles, as the slate aggregate properties were within the range of those of conventional ceramic tiles (Campos et al et al., 2004).

Despite this evidence and successful local use in road construction projects in North Wales (Dawson et al, 1993), slate is still viewed as being inferior because of its shape. Further testing's were performed on the roads in North Wales where slate aggregate was used to firstly measure the sub-base reaction modulus using plate bearing tests and secondly to perform grading analysis of the sub-base slate aggregate material after seven years in service. The reported reaction moduli in the sub-base varied from 378 to 646 MPa confirming the good condition of the slate aggregate (Goulden, 1992). The reported degradation of the slate aggregate material was minor and at lower levels than expected for conventional aggregates, it was also noted that the material remained stable during reconstruction of deficiencies caused by mix macadam comprising conventional aggregate (Dawson et al, 1993). For example despite that Goulden (1992) in his thesis reported that slate aggregate showed exceptional performance even better than most conventional aggregates, he also reported that the particle crushing resistance appeared in his testing to be at the limit of what may be applied in pavements, but that the values he obtained from the Ten per cent Fines were on the contradictory very good. Therefore, regardless of the slightly low strength obtained in the Aggregate Crushing Value test, this was not present in the Ten per cent Fines Value test and the aggregate had good performance in the field (Dawson et al, 1993).

Goulden (1992) applied conventional testing and some of the slate aggregate weaknesses in his thesis have been addressed in Woodward et al (2004) non-conventional testing's. The conventional testing results (Goulden, 1992, Dawson et al, 1993) noted that the high flakiness index did not appear to cause increased degradation or instability during compaction or after it. Woodward et al (2004) documented similar issue in their research, reportedly that few flaky particles broke during compaction, however, they also noted that this abnormally did not re-orientate to form layers or make the unbound layer any more difficult to compact. The type of compaction i.e. kneading versus impact also appears to have an effect. It is suggested that this may have an influence on impact types of testing being carried out as part of a quality control process on-site.

The wheel-tracking test Woodward et al (2004) implemented in their research showed that flaky slate performed identical to the best basalt in Northern Ireland in terms of resistance to permanent deformation. Compared to the limestone Type 1 aggregate assessed, slate was found to have a 'greater wet density at a specific CIV' (Woodward et al2004). Considering that density is a function of compaction, slate Type 1 aggregate will have a lower CIV than limestone after a similar amount of compaction. This is proven by the fact that laboratory investigation has determined a CBR – CIV correlation for slate Type 1 aggregate, 'comparison with published research findings for other unbound materials confirms that CIV underestimates CBR' (Woodward et al2004).

Considering that a distortion of an unbound layer causes further distortions with overlying layers and that these distortions can be reduced by using a high quality aggregate which will also help in achieving a good compaction. Furthermore, if we use thick aggregate and asphalt layers we can also reduce the stresses, nonetheless, reliance on thicker layers makes a design un-economical. Furthermore, with the new carbon emission reduction targets there is now significant pressure to recycle and use secondary aggregates. Despite the problems of variability, sorting and relatively poor properties there are millions of tonnes of secondary unbound aggregates usage. Still, many of the recycled unbound materials have either never been or have had limited use in the UK until the past few years e.g. unbound construction and demolition waste aggregates (C&D waste) (Lancieri et al et al., 2006). In benefit of those aggregates the DoT specification requirements now include an increasing range of options of what would formally have been regarded unsuitable.

Slate waste, a secondary aggregate from an industrial process, is one such material that has proven very successful locally over many years in North Wales and shown in the laboratory to perform well (Dawson et al, 1993). However, the use of slate waste has been limited in quantity and in area, with approximately 0.5 million tonnes currently being used, representing a small percentage of the annual production, leaving untouched all the stockpiled material (Dawson et al, 1993).

The Effect of Moisture content on Compaction

Increasing moisture in a pavement can have a disruptive effect on the integrity of the unbound layer. Sherwood (1994) classified the slate aggregate as a material with a high potential for usage in pavement foundation. More specifically he considered the slate aggregate as a material with high potential usage in pavement foundation as Unbound Capping Layer and Unbound Sub-Base, and some potential as a Cement-Bound material (Sherwood, 1994).

The effect of increasing amounts of moisture was also investigated by using gyratory compaction (Woodward et al, 2004). The result from these testing's have proven that the void content decreases with increasing number of gyrations or compactive effort and that for any given degree of compaction, the void content decreases with increasing moisture content. This test's also showed that the slate aggregate density is related to moisture content and degree of compaction. The greatest wet density, measured using both nuclear Density Meter and Clegg Impact Value, corresponded to the moisture content of 3 to 4% moisture content. Nevertheless, they also noted that at the higher moisture contents excess water was squeezed out of the base during compaction and that levels of compaction achieved on-site would probably be less than those obtained in the confined mould during laboratory compaction.

Comparison of Impact and Kneading Compaction

Woodward et al (2004) used the Marshall impact as it offers less change in grading due to particle breakage compared to Kango vibration. However, in their study they also considered an alternative method of laboratory compaction as the kneading action caused during gyratory compaction better simulates the action of a roller than the sudden impact of Marshall or aggressive Kango vibration. They assessed the reduction in layer thickness caused by compaction to find the possible reduction in layer thickness during rolling or other types of compaction. The testing's they performed showed that slate compacts at different rates depending on the method of compaction used i.e. it appears to compact quicker using impact compaction.

Assessment of Construction and Post Deformation

Post compaction of unbound layers causes issues with over lying layers. Therefore, Woodward et al (2004) applied the wheel-tracking test to simulate stress conditions that could result in permanent deformation under a moving wheel load. Slate aggregate was compared to three unbound aggregates of centre specification Type 1 grading envelope at optimum moisture content. The results show slate at both 0 and 4% to be comparable in performance to the best basalt aggregate assessed. This is despite its flaky particle shape characteristics. The two remaining basalt aggregates were chosen to demonstrate the ability of this wheel tracking test to discriminate between aggregates in terms of performance. This testing clearly shows slate to have good performance in terms of resistance to permanent deformation and load bearing properties. The results are strengthened by the further testing's performed on the slate aggregate used as a sub-ballast for building roads in North Wales where the grading analysis of the slate aggregate material after seven years in service was reported in good condition or even better condition than expected from a conventional aggregate (Dawson et al, 1993).

A number of experiments have been performed to assess the effect of moisture content on the wetting of slate particles properties such as compacted height, density and void content during compaction.

The Effect of Grading on Compaction

Unbound aggregates may become segregated and if used on-site differential compaction could later create complications with the finished highway. This is confirmed by a research which found that different aggregate types and grading creates problems such as the migration of plastic fines (Ali et al, 2010). This was tested by Woodward et al (2004) who analysed data from a bulk sample of slate separated to obtain single size aggregate combined to form test samples with a grading corresponding to the coarse and fine Type 1 limits. The test showed that the coarse graded test samples produce a slightly denser material. However, the difference in density between the two grading limits is less than 5.

4. Compaction trials specific for the Welsh Type 1 Slate Aggregate

Slate aggregate is concentrated in remote areas with North Wales being 'by far the main producing area' (Dawson et al, 1993). Woodward et al (2004) performed compaction trials for Welsh slate aggregate using slate aggregate as Type 1 sub-base material. Prior to this testing's Goulden (1992) performed a comprehensive conventional testing programme including load triaxial tests on Welsh slate aggregate. As mentioned above when slate aggregate tested using conventional impact testing methods the testing may give a different impression of its compaction compared to a more conventional type of aggregate, and this research reviews the findings from conventional and non-conventional testing methods. Nevertheless, even the conventional testing's Goulden (1992) performed and executed on slate aggregate in accordance with British Standards Institute (BSI, 1985, BSI, 1990, BSI, 1980) showed an 'exceptional performance even better than most conventional aggregates'. The conventional mineral testing's for example showed that the slate aggregate is fairly consistent in properties regardless of the source, with the water absorption being very low at 0.2% to 0.3% which presents high durability and very high performance in the soundness tests (Goulden, 1992).

Woodward et al (2004) considered typical new road construction and trench reinstatement. Their first trial site was Llangefni, Anglesey for construction of the road foundation and footway and second site was located within Penrhyn Quarry, Gwynedd for road sub-base and trench reinstatement applications. Regardless of the site as Dowson and Nunes (1993) reported slate aggregate is consistent despite the source from which the material is supplied. Woodward et al (2004) used three pieces of test equipment. Firstly they used the Clegg Impact Soil Tester to take multiple readings of CIV at compaction intervals, on different layers and after compaction by different pieces of equipment. Secondly, Nuclear Density Meter (NDM) was used to measure wet density and moisture content of the material at each compaction interval, on different layers and after compaction by the different pieces of equipment. Finally, Sand Replacement testing was carried out on compacted layers to verify the NDM density measurements. The slate was sampled for laboratory verification of grading analysis and moisture content.

Woodward et al(2004) carried out the Anglesey compaction testing at 4 areas within the site. At each test location the bulk density was first determined using the NDM (BS 1377, 1990). A series of 6 CIV tests were then carried out in accordance with the site test procedure given in the Clegg operations manual (Deakin, 2001) The mean 4th impact value was reported as the CIV for each test location. At the Penrhyn Quarry trial testing's they followed guidelines set out in ASTM D 5874-95 (ASTM, 1995).

The assessment of density and strength properties of unbound granular materials used to construct road bases, sub bases and trench reinstatements is critical for good design practice. The California Bearing Ratio (CBR) test is used extensively for assessing these properties. However, the test is time consuming and expensive especially when carried out on site. The Clegg Impact Tester is a fast and inexpensive alternative to CBR testing (Deakin,

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2001). Existing research has shown Clegg Impact Value (CIV) to correlate well with CBR for a wide range of materials (Al-Amouki et al, 2002, Clegg, 1980, Coghlan et al, 1987). However, it has been stressed that these correlations are material specific and recommend that it is better to establish correlations between CIV and CBR for individual material types rather than rely on generalised correlations. This section summarises testing's performed to calculate the equations relating CBR and CIV for Welsh slate Type 1 aggregate (Woodward et al, 2004). The data is compared to a good quality Carboniferous limestone Type 1 aggregate.

Analysis of CIV and CBR Data

- The wet density was measured using the volumetric method, which allowed CBR to be correlated with CIV for slate at the range of moisture contents.
- The tests showed very good correlation between wet density and Clegg.

The Clegg Impact Soil Tester

- The Clegg Impact Soil Tester provides a quick simple means for assessing the compaction of unbound materials such as aggregate and soils (Deakin, 2001).
- The tests showed that the Clegg gives a lower Impact Value result for slate than for limestone.

Laboratory Investigation

- Labaratory comparisation of wet density, moisture content and compaction conditions between CBR and CIV of Type 1 Welsh slate and carboniferous limestone using the Force/Penetration curve set out in BS EN 13286-47: (2004).

Surprisingly, this testing's found that Type 1 unbound slate aggregate does not perform equally to conventional unbound materials (Dawson and Nunes, 1993, Woodward et al2004). The results showed that the unique flaky shape characteristics of slate positively affect its performance as unbound aggregate i.e. most notably compaction, deformation and load bearing properties. This has been confirmed in both the laboratory and on-site trials.

5. Estimates of the Slate Aggregate quantities

Large tips of slate aggregate have accumulated over the past 200+ years in North Wales These tips are potentially a good source of material (ODPM, 2002). According to Dawson and Nunes (1993) the process of slate quarrying results in a 20 to 1 waste to final product, creating large quantities of slate waste tips that can be used as an aggregate. The (ODPM, 2002) also reported that 19tonnes of slate waste is produced per tonne of usable slate and that between 90% to 95% of the quarried slate is being disposed.

There are various estimates of those quantities, for example Dawson and Nunes (1993) estimated 400 to 500 Mt usable tips stockpiled and new 6 Mt arising annually in North Wales (Dawson et al, 1993). The letter report commissioned by ARUP (2001) confirmed those estimates with calculating nearly 6 Mt of arising's generated in North Wales of which only 275,000 tonnes was being used as aggregate (ARUP, 2001), or 4.5% of the arising's (Arup, 2001). WD (2005) documented that there are 700Mt of Slate Aggregate in reserves and growth of 6Mt annually which is secured for the foreseeable future (WD, 2005). Even more recent reports such as WRAP (2005) reported 6.3 Mt arising, consecutively WRAP (2010) reported 6.33 Mt arising and 456.5 Mt in existing usable stockpiles (WRAP, 2010). Complimenting ARUP (2001) report, WRAP (2010) stated that although all 100% of arising's of Slate Aggregate are suitable for aggregate use only about 0.56 Mt is being used as aggregate and 0% being used for non-aggregate purposes.

Trends in aggregate use: although increasing, utilization is still low because of the economics of slate waste, mainly dominated by the distance of stockpiles from the main aggregate markets. For these reasons aggregate use has only occurred over the last 20 years on a very local basis. With exemption from the Aggregates Levy, transporting the material is now becoming commercially feasible [ODPM, 2002]. Future potential: development work such as thermal processing in a rotary kiln to produce lightweight aggregate also increases the scope for further aggregate utilization. The possible improvement to rail infrastructure in North Wales could make slate waste cost effectively available nationwide (ODPM, 2002). In December 2000, Arup and its sub-consultants were appointed by the National Assembly for Wales to carry out the research contract entitled "North Wales Slate Waste Tips – A Sustainable Source of Secondary Aggregates?". The aim of the research was 'to evaluate the practical potential for the use of slate waste tips in North Wales as a source of secondary aggregates.' (ARUP, 2001). The following observations come from that WAG commissioned report:

- on the basis of material suitability, slate waste could supply some 50% of UK crushed rock sales. This amounts to a market size of some 59 million tonnes/annum, well in excess of current waste generation rates
- the use of slate waste as a secondary aggregate encompasses the current policy areas of mineral planning, planning, waste, transport and sustainability. Policy is highly supportive, at all levels, of the use of slate waste as a secondary aggregate, provided its exploitation and transport are sustainable

Conclusion

In conclusion, this paper summarised findings from existing literature on the performance of the slate aggregate. The paper outlined the slate aggregate in terms of suitability as a material, and confirmed that, with a certain amount of processing slate aggregate can be used for a number of usages, including as a secondary aggregate. However, its economic viability, without a low-cost rail transport is questionable. The environmental damage from transporting the slate aggregate from the quarries in North Wales to marketplaces in urban areas are also triggering questions on the environmental sustainability, especially because the journey would lead through the Snowdonia National Park. Converting the secondary aggregate into a higher value material at the quarry and transporting the new product could create more favourable scenario for removing the slate waste from Blaenau Ffestiniog. Highly skilled and available labour is available in abundance in the area surrounding the quarry. This would also trigger new opportunities in an area in desperate need for employment. But without a coordinated joint effort from government and private sector, its hard to see how this could materialise.

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