Concrete mix utilising oil shale ash

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ABSTRACT

This paper reports on-going work within the framework of the EcoCrete Eco-innovation project, in which novel approaches are being developed to productively utilise Estonian oil shale ash waste. The influence of the ash on fresh and hardened properties of concrete is presented. Reduced particle size of the ash is seen to improve the rheology of a mix and rate of strength development. In the context of sustainable development, it is not only the cement content of a mix that is relevant but the quantity of concrete used; use of higher-performance concrete enables reduction in size of structural components which leads to reduced consumption of materials, not only cement, but also aggregates. Based on a small set of test data, the mix design toolset developed within the project enables the performance of alternative mixes to be predicted within an accuracy of around ±10%.

Key words: Oil shale, ash, cement, concrete properties, design toolset

1. INTRODUCTION

1.1 Oil shale production

Oil shale is used by the energy sector in many countries including Brazil, China, Estonia, Jordan and its utilisation is being seriously considered by several others, for example Australia, USA and Canada. In the production of electrical energy, 55 to 75 kg of oil shale ash (OSA) is produced per 100 kg of oil shale fuel. Oil shale is used to produce more than 90% of the electricity in Estonia and approximately 1 billion tons of oil shale has been mined during the last 80 years. Disposal of the waste ash is a huge problem with leaching from the unsightly ‘mountains’ of waste resulting in pollution of rivers and lakes. Utilisation of oil shale ash to replace a proportion of the cement content in a concrete mix demonstrates how industrial waste can be beneficially used to control product properties and improve the environment /Vimmr/.

1.2 Cement replacement

It has already been proved by various research programmes that OSA can be utilised in the manufacturing of cement clinkers /Cobb, Oymael/. Up to 15% of OSA can be used with a typical Portland cement clinker without significant effecting the main properties of cement /Al-Otoom/. Direct substitution of cement by OSA in a concrete mix is an important step towards improvement of concrete sustainability, both by reducing the carbon footprint and, at the same time, utilising wastes causing environmental problems, quite apart from the potential cost savings and improvements in durability of the concrete.

1.3 Chemical composition of OSA in Estonia

As for coal fly ashes, the chemical composition of OSA can vary considerably. It has been found that composition and particle size distribution depends on the origin of the oil shale and temperature of combustion, together with the collection point i.e., stage of the flue gas cleaning cyclones/ electrostatic precipitators. This explains why the findings of various authors appear sometimes to be contradictory.
With specific reference to Estonian OSA, the influence of particle grading on chemical composition is shown in Table 1. It can be seen that smaller particles are generally associated with a smaller CaO content.

Table 1 - Composition and properties of Estonian OSA (%)

Component	Range of chemical composition		
	course -grained	medium	fine
CaO	50-57	40-53	30-48,5
SiO_2	19-29	19-34	25-34,5
SO_3	3,2-3,8	4,0-6,7	6,0-9,5
MgO	4,0-5,5	3,5-5,0	-
CaO_{free}	20-32	16,5-28,0	7,5-25,0
Size of particles	Limit range of grades		
< 30	2-12	20-62	65-95
30-100	18-70	25-62	5-28
> 100	30-80	5-30	0-10

2. CONCRETE PROPERTIES

OSA can, to a certain extent, influence both the fresh and hardened concrete properties. For instance, incorporation of OSA in a mix can help to reduce concrete expansion due to alkali-silica reaction. It has been found that shrinkage and creep can have the same values when 15% of OSA is added to ordinary portland cement. However, when 30% of OSA is added, shrinkage and creep generally have higher values.

2.1 Strength development

Corresponding tests showed that concretes in which cement was partly replaced by OSA usually have slower development of compressive strength and also slightly lower strength values after 28 days in comparison with a reference concrete mixture without OSA.
Typical curves representing strength development of concrete for different mixes are illustrated in Fig.1.The slow development of strength is caused by a relatively high content of SO_3.

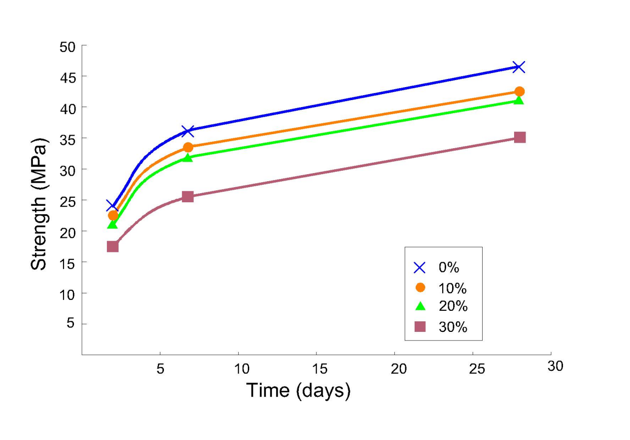

Figure 1 – Compressive strength development

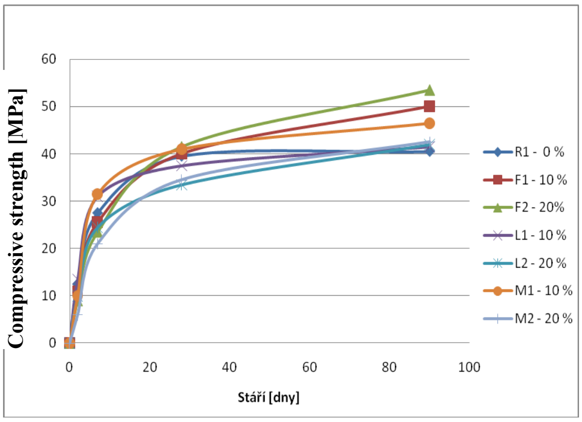

Figure 2 – Strength development

2.2 Particle size effect

Figure 2 shows the influence of micronising of particles of fly ash (FA) on strength development within 90 days. A reference concrete mix without ash (R) is compared with mixes when 10 or 20% of cement is replaced by ash from two different Czech power plants (M and L) and micronised ash from Finland (F). The results indicate that benefits result in the longer term i.e., for the mixes using micronised ash, strength continues to develop after 28 days. Replacing a proportion of cement by fly- or oil shale-ash can improve workability, making the rheology of a mix easier to control, especially with micronised or classified small-size ash. Compared to the reference mix, R, which had a slump of 80 mm after 90 minutes, mixes F (with either 10 or 20% cement replacement by ash) had slump of 110 mm, each mix using the same quantity of Sulfonan™ superplasticiser. Alternatively, the dosage of the superplasticiser necessary to achieve a given workability can be reduced, resulting in cost savings. Interpretation of results is complicated by the chemical interactions between superplasticiser and the cement/ ash. Work is in progress to study the particle size effect of OSA in more detail.

3. SUPPLEMENTARY CEMENTITIOUS MATERIALS (SCM) AND SUSTAINABLE DEVELOPMENT

Reduction of cement content of a mix does not *per se* result in concrete of reduced environmental impact. /Aïtcin and Mindess/ highlight that a 75 MPa unreinforced concrete involves 50% less cement and only one-third as much aggregate compared to a 25 MPa concrete used to build a column supporting the same static design load. Compared to this simple example, the savings in cement and aggregate are less impressive for concrete elements working in flexure but, nevertheless, are conservatively estimated to be of the order of 20 to 25%.
The point being made is that sustainable concrete requires a performance-based design approach taking full account of the material composition and resulting concrete properties. In the above simple example, it would be wasteful to use the 75 MPa concrete when the design load is only 25 MPa. However, if the design takes advantage of the75 MPa strength by using less concrete, then the material resources are being beneficially used.
Comparing a mix A with a mix B both having the same water content, the latter involving replacement of a proportion of the cement of the former with oil shale ash or other SCM, the compressive strength at early age will generally be somewhat less for the latter. However, even if compressive strength is the parameter of interest, it would be a mistake to conclude that cement is ‘better’ than the SCM. The required strength can readily be achieved by a reduction in the water/ binder ratio (*w/b*); let us refer to this as mix C. Hence, the only meaningful comparison is between mix A and mix C. Mix C will use more cement than mix B but less than for mix A. The cost of any additional superplasticiser that may be required will generally be offset by the saving in cost of cement. In this way, a mix C results which achieves the required performance (compressive strength, in this simplistic example) whilst using a reduced quantity of cement. A superior concrete results, since cement — apart from being the environmentally-unfriendly component of concrete in terms of CO2 emissions during manufacture — is also associated with many of the durability-related problems of concrete /Neville/. We cannot make concrete as we know it without portland cement, but we should minimise the cement content, balancing technical advantages and disadvantages together with cost. Cement plays an important role as far as reinforcement corrosion prevention is concerned.

4. MIX DESIGN TOOLSET

Within the EcoCrete Eco-innovation project, design tools are being developed to optimise mix designs utilising locally-available materials, including industrial wastes such as oil shale ash.
From the starting point of initial selection of the considered most appropriate locally-available materials of the particular batching plant, the performance of trial mixes each having the same water content whilst varying in the proportion of cement replaced by the SCM are evaluated (for example, 15% and 30% replacement, together with a 'cement-only' control mix). For each binder combination, mixes differing widely in water/ binder ratio (for the purpose of example, say 0.50 and 0.35), are compared. The results of such tests provide input data for a model characterising the materials being used. It has been found that compressive strengths of mixes having other intermediary water/ binder ratios can be predicted with an accuracy of around ±10% using this approach.
The model considers the SCM as having an efficiency factor, f , whereby a mass f of the SCM is equivalent to a mass k f of cement in terms of strength development, the effective water/ binder ratio is then w/[c+k f]. It has been found that the well-known Bolomey equation for strength development must be modified to account for a time dependency of the efficiency of the SCM, i.e., at early age the efficiency of oil shale ash is somewhat lower than for cement, whereas at 56 days it approaches unity and continues to increase with age of the concrete.
The approach is being extended to encompass durability and other performance-related requirements for the concrete.

5. CONCLUSIONS

1. The early age strength of mixes incorporating oil shale ash may exhibit lower values for the same *w*/*b* because of a slow pozzolanic reaction. However, the same early strength, if necessary, can be achieved by increasing the binder content, keeping the effective *w*/*b* ratio *w*/[*c*+*k f*] and the water content constant i.e., increasing the binder content to compensate for the reduced efficiency at early age.
2. It is considered that the rate of the pozzolanic reaction can potentially be increased based on micronising the oil shale ash, although this is a topic subject to ongoing investigation. This approach offers the potential to further reduce cement and overall content of binder.
3. The longer term pozzolanic reaction results in the concrete continuing to gain strength as a result of incorporation of oil shale ash in the mix.
4. Replacing a proportion of cement by oil shale ash can improve workability, making the rheology of a mix easier to control, especially with micronised or classified small-size ash.
5. When comparing mixes with and without SCMs such as oil shale ash, a proper basis of comparison must be defined i.e., it is necessary to compare mixes providing the same performance required for the application.
6. Reduction of cement content of a mix does not *per se* result in concrete of reduced environmental impact. Rather, the objective should be design and produce 'better concrete' providing the most effective and efficient solution for the specific project requirements.
7. Mix design tools requiring relatively simple input data from a small number of trial mixes using locally available materials, including industrial wastes such as oil shale ash, can predict the performance of new mixes with a accuracy of around ±10%.

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