MECHANICAL AND PHYSICAL PROPERTIES OF CONCRETE CONTAINING FGD WASTE

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Abstract

The paper is part of a wide ranging research project on the optimum use of waste from the dry and semi dry flue gas desulphurisation (FGD) processes in concrete. It examines the influence of a typical simulated desulphurised waste (SDW) on the physical and mechanical and physical properties of concrete. SDW was chosen due to the wider variability in the composition of actual FGD waste. Two binder systems were investigated (i) cement and SDW (C-SDW) and (ii) cement, slag and SDW (C-S-SDW). The SDW content ranged from 0-70% and the slag from 0-90% as partial replacement of the cement. The properties examined included compressive and flexural strength, water absorption, shrinkage and expansion. The results showed that replacing cement with SDW beyond 20% systematically reduce strength. An increase in SDW reduces shrinkage. The presence of small amounts of slag allows the use of high proportions of SDW. The use of desulphurised waste in concrete applications is possible as adequate strength can be achieved.

Keywords: concrete technology & manufacture, recycling & reuse of materials, environment.

1. Introduction

The presence of certain amounts of gypsum (G) in concrete affects its strength. Lerch (1946) reported that gypsum in cement generally increased strength. However, the optimal G content depends mainly on the clinker used. The three main factors influencing optimum G content are fineness, C_3A content and the alkalis (Na_2O, K_2O) present in the clinker used. The presence of sulphate in blended cement containing slag, fly ash and silica fume improve performance (Poon et al 2001; Wang & Song 2013).

Bentur (1976) and Shiyuan (1982) reported that incorporating between 2-4% G in cement paste leads to an increase in strength whereas reduction occurs beyond this level. Increasing the G content increases the C/S ratio of the C-S-H formed, which corresponded to a decrease in strength of the C-S-H gel. The strength of mortars was found to decrease as the G content increased, irrespective of the curing condition.

The large variation in composition of coal combustion wastes form dry and semi-dry desulphurisation process means that the strength properties of binders containing such wastes are significantly different. There have been attempts to investigate the strength of such materials in cement-based systems and non-cement based systems, however, the results seem specific to each investigation (Jeppesen 1990). Demirbas and Aslan (1999) reported that using desulphurised wastes, reduced the early strength however, the strength at 28 days was either equal to or greater than the reference. It was suggested that the strength was dependent on the composition of the waste, and an increase in the $SiO_2+Al_2O_3+Fe_2O_3$ (SAF) resulted in a strength decrease. Wastes containing high SAF contents are generally classified as pozzolanic and, therefore, the positive effects of these ashes may not have been observed during the first 28 days. The wastes that performed the best were low in SAF and consisted mainly of CaO and are similar to fly ash with high lime contents (ASTM Class C), which exhibit both cementitious and pozzolanic properties.

Spray dry absorption wastes (SDA) are a semi-dry waste and consist of fly ash, sulphates and sulphites. Cornelissen (1991) reported the strength of concretes containing simulated SDA waste with various sulphate-sulphite ratios. As with other desulphurised wastes, the setting times were slightly retarded meaning that strength development was slightly slower. After 28 days, the strength of the SDA mixes was significantly lower than the reference and increasing the sulphate-sulphite ratio decreased the strength. Drottner and Havlica (1997) indicated the strength development properties of mortars containing fluidised bed combustion ash (FBC) and found the strength is dependent on the content of FBC in the mix and the age of curing.

In this paper, an experimental investigation was carried out to evaluate the properties of concrete containing FGD waste to partially replace the cement. Due to the wider variability in compositions of actual FGD waste, simulated desulphurised waste (SDW) was used which was a blend of fly ash and gypsum. In addition, the influence of including ground granulated blastfurnace slag in these binder systems on concrete properties was investigated. The properties determined were consistence, density, compressive and flexural strength, water absorption and length change.

2. Experimental

2.1 Materials

A standard 42.5N cement (C) and fly ash (FA) conformed to BS12: 1996 and BS3892: 1997 respectively. Ground granulated blastfurnace slag (S) conforming to BS6699: 1992 and wallboard grade quality Gypsum (G) with a $CaSO_4.2H_2O$ purity of 95% were used. The typical simulated desulphurised waste (SDW) was a blend of 15% gypsum and 85% fly ash to achieve an SO_3 content of 8.87% by weight (Khatib et al, 2008). The fine aggregate used was class M sand in accordance with BS 882:1983. The coarse aggregate was crushed 10mm single sized aggregate in accordance with BS 882:1983. Further information on chemical and physical properties of the constituent materials is given elsewhere (Mangat et al, 2006; Khatib et al, 2013).

2.2 Mix proportions

A total of 13 mixes were used to determine the mechanical and physical properties of concrete containing SDW. The proportions by weight of binder to fine aggregate to coarse aggregate were 1:2:3.5 respectively. The water/binder was 0.5. The binder consists of cement and all cement replacement materials. The replacement materials include slag (S) and simulated desulphurised waste.

Mix 1 represents a reference mix [REF(100_c)] where the binder is 100% cement. Mixes 2 to 7 contain different blends of cement (C) and a typical simulated desulphurised waste (SDW) and were referred to as C-SDW. The cement was replaced with increasing levels of SDW from 0 to 90%. The proportion of the SDW was 85% fly ash and 15% gypsum. Table 1 shows the proportion of the mixes investigated. The mix ID (column 2) in mixes 2 to 7 represents the constituents of the binder. For example, mix 70_C30_{SDW} represents a binder containing 70% cement and 30% of SDW by mass of binder. Columns 3 and 4 show the cement (C) and typical simulated desulphurised waste (SDW) contents respectively.

Mixes 8 to 13 contain different blends of C, S and SDW (C-S-SDW blends). The C content was kept constant at 10% to initiate the reactivity of the slag and to maximise waste content. The slag content ranged from 90 to 20%, and the SDW content ranged from 0 to 70%. Table 2 shows the proportions of C-S-SDW mixes. The mix ID (column 2) of mixes 8 to 13 represents the constituent of the binder. For example mix $10_C70_S20_{SDW}$ represents a binder containing 10% cement, 70% slag and 20% SDW by weight of binder. Columns 3 to 5 show the C, S and SDW content respectively.

2.3 Casting

For each mix, eighteen 100mm cubes, six 75mm cubes and four 75mm x 75mm x 300mm prisms were cast in steel moulds. After casting, all specimens were placed in a mist curing room at 20ºC±1ºC and 95%±5% relative humidity until demoulding. For most specimens the initial mist curing was for 24 hours, however, several specimens required a longer initial period due to an increase in setting times. Theses generally included C-SDW blends that contained large amounts of gypsum and all the C-S-SDW blends (i.e. mixes 8-13), in which case the specimens were left for a further 24 hours in the mist room. After demoulding, all cubes and two of the prisms were cured in water at 20ºC until testing. The other two prisms were continuously cured in air at 20ºC±1ºC and 60%±5% relative humidity.

2.4 Testing

The consistence of concrete was measured using the slump and Vebe tests in accordance with British Standard (BS EN 12350-3, 2009) and (BS EN 12350-2, 2009) respectively.

Compressive strength was conducted on the 100mm cubes at 1 day, 7, 28, and 365 days according to British Standard (BS EN 12390-3, 2009).

Water absorption was carried out on the 75mm cubes. Measurements were taken at 28, 90 and 365 days. At the desired age, samples were removed from the water, oven dried at 105ºC±5ºC until a constant mass was achieved. This took approximately 48 hours. The samples were then cooled for 24 hours in a desiccator over silica gel crystals. After drying the samples were submerged in water to a depth of 25mm±5 mm below the water surface. The increase in mass due to absorption of water was then recorded after 30 minutes. The water absorption was expressed as a percentage of the original dry mass of the sample.

Drying shrinkage and expansion were conducted on the prisms which were cured in air at 20ºC, 65%RH and in water respectively. Two steel demec discs were fixed to each of the longitudinal faces of the prisms at a spacing of 200mm. Therefore, each measurement is the average of eight readings. At the end of the length change monitoring period, flexural strength test was carried out on the prisms in accordance with British Standard (BS EN 12390-5, 2009).

3. Results

3.1 Consistence

Figure 1 (a & b) shows the consistence of concrete containing C-SDW and C-S-SDW blends respectively. Both slump and Vebe time are plotted with respect to SDW content. Generally, an increase of simulated desulphurised waste (SDW) content reduced consistence. Based on the Vebe time recorded, an increase in the SDW content from 0 to 70% changed the mix from a stiff plastic to an extremely dry mix. The replacement of cement with S in mix $10_{C}90_{S}0_{SDW}$ increased consistence (Figure 1-b). The consistence of the C-S-SDW concrete was reduced when S was replaced with increasing levels of SDW. The consistence was significantly reduced when the SDW content exceeded 40%, after which the mix classification goes from stiff to extremely dry based on the Vebe time test (Neville 2011). The consistence of C-SDW and C-S-SDW concretes is similar for equivalent SDW contents.

3.2 Compressive strength

The influence of SDW content on the compressive strength of concretes containing C-SDW blends (mixes 1-7) at the different curing times is shown in Figure 2. The use of 10% SDW as partial replacement of cement is beneficial especially with regard to long-term strength in that the strength is higher than the reference. At 20% SDW replacement the long-term strength is equivalent to the control. Replacement levels beyond 20% SDW cause a gradual decrease in strength with increasing amounts of SDW. At 90% SDW the long-term strength is 75% less than the reference. The relative strength (RS) to the control for the majority of C-SDW blends decreased during the first 7 days of curing. Between 7 and 90 days of curing, there is large increase in RS for all C-SDW concretes indicating higher rate of strength development. After 90 days the rate of increase in RS is slowed down but still higher than the reference.

Replacing cement with 10% SDW (mix 90_C10_{SDW}), slightly retards the strength up to 7 days compared to the reference. After 7 days, an increase in strength was observed, and the strength surpassed the reference between 28 and 90 days. After 90 days, the strength continued to increase and at 365 days, it was 20% higher than the reference.

An increase in the SDW content from 10% to 40% decreased the RS. A negative effect on the rate of RS development was observed during the first seven days. Between 7 and 28 days, a large increase in RS was observed. After 90 days, the rate of increase in RS was similar to the mix containing 10% SDW, and greater than the reference mix. At 20% SDW replacement, the strength was equal to the reference mix at 365 days. Mixes containing 30% and 40% SDW exhibit a RS of 90% and 85% respectively at 365 days of curing.

The RS at of mixes 30_C70_{SDW} and 10_C90_{SDW} during the first seven days, was very low. Between 7 and 28 days, both mixes exhibit a similar rate of increase in RS, which was greater than that exhibited by the reference. Between 28 and 90 days, the mix containing 70% SDW, exhibited a similar rate of RS development as other mixes but the 90% SDW mix did not exhibit an increase in RS.

The compressive strength of concretes containing C-S-SDW blends are shown in Figure 3. In general, all mixes exhibit a decrease in strength compared to the reference at all ages. At 7 days, all C-S-SDW concretes exhibit an RS of approximately 30%. After 7 days, the increase in RS is negligible for all C-S-SDW concretes, and at 365 days the RS is between 35% and 50%.

3.3 Flexural strength

Figure 4 (a) and (b) show the flexural strength of C-SDW and C-S-SDW concretes cured in air at 20ºC and 65% relative humidity, and in water at 20ºC. The tests were carried out at 570 days on samples used to measure length change. The strength is plotted with respect to SDW content. The figure shows that water cured samples exhibited greater strength than samples cured in air. An increase in SDW content resulted in a larger difference between the strength of water and air cured samples. For example, the reference mix exhibited a difference of about 30% between the flexural strength of air and water cured samples, whereas, the mix containing 70% SDW (30_C70_{SDW}), exhibited a flexural strength in water more than twice that of air cured samples. It is noticeable that the trend between strength and SDW content was similar for flexural strength (Figures 2 and 4). In addition, water cured mixes containing up to 40% SDW exhibited a higher flexural strength than the reference mix. Under air curing, only the 10% SDW concrete showed a flexural higher than the reference mix.

The strength of C-S-SDW concretes cured in water was greater than under air curing (Figure 4-b). There was little difference in the flexural strength for all the C-S-SDW concretes (excluding the reference) when cured in air or water. Water curing resulted in higher flexural strength compared with air curing.

3.4 Water absorption (WA)

Figure 4 (a) and (b) shows the influence of SDW content on the water absorption (WA) of respectively C-SDW and C-S-SDW concretes at 28 and 365 days. An increase in the SDW content generally increased the WA. Concrete is defined to have low, medium and high absorption if the WA is below 3%, between 3% and 5%, and above 5% respectively (Concrete Society 2008).

At 28 days the WA increased with increasing SDW content. Concretes with SDW contents of 0 or 10% exhibit low WA. Mixes with SDW ranging of 20 to 40% exhibit medium WA whereas high WA is obtained at 70% SDW. All SDW concretes exhibit a reduction in WA between 28 and 365 days, the 365 days values being under 3%. For the mix containing 70% SDW, there was little change in WA between 28 and 365 days, giving a value of about 6%. The trend in the absorption is similar to the of total pore volume reported elsewhere (Khatib et al, 2013; Khatib et al, 2014)

For the C-S-SDW concretes (Fig. 4-b), the WA was in the range of low to medium at all ages based on limits set down by the concrete society. The values of WA decreased slightly with age of the C-S-SDW concretes. The increase in SDW content made a modest increase in WA.

3.5 Drying shrinkage

Figure 6 shows the drying shrinkage-time relationship for C-SDW concretes. For all mixes, the majority of shrinkage occurs during the first 30 days. After that shrinkage reduces with increasing SDW content. At 90% SDW, the long-term shrinkage is about 30% of the reference.

Figure 8 shows the change in drying shrinkage-time relationship for C-S-SDW concretes. Most of the drying shrinkage occurred during the first 28 days. Unlike with C-SDW concretes (Fig. 6) there appears to be no relationship between drying shrinkage and the SDW content of the C-S-SDW blends.

The effect of SDW content on the 28 and 365 days drying shrinkage for concretes with and without S is shown in Figure 7. An increase in the SDW content of C-SDW concretes shows a decrease in shrinkage, however, the shrinkage of the C-S-SDW concretes shows no clear trend.

3.6 Expansion

Figure 8 shows the expansion-time relationship for C-SDW concretes. Most expansion for C-SDW concretes occurred during the first 28 days. After 90 days, there is hardly any expansion. Generally, an increase in the SDW content increased the expansion of the concretes. There is no significant expansion up to 20% SDW content. Expansion of 1100µs was observed for mix containing 70% SDW.

Figure 9 shows the expansion with time for C-S-SDW concretes. As in Figure 8, most of the expansion occurred during the first 28 days followed by hardly any expansion. There was no apparent relationship between SDW content and expansion. During the first seven days, mixes containing 10% and 40% SDW exhibit shrinkage, whereas, mixes containing 20%, 30% and 70% SDW all exhibit expansions. The mix containing 70% SDW ($10_{C}20_{S}70_{SDW}$), exhibits the largest expansion of 500µm.

4. Discussion

4.1. Consistence

The consistence of C-SDW and C-S-SDW concretes, as measured by Vebe time, was significantly reduced once the SDW content exceeded 20%. An increase in the SDW content from 40% to 70%, and subsequently to 90%, resulted in the mix changing from a stiff mix, to a very stiff mix, and then to an extremely dry mix (Concrete Society 2008). The SDW contains approximately 85% fly ash, which is known to increase the consistence of cement mixes (Bai et al 1999). The increase in consistence is generally attributed to the spherical nature of the fly ash particles, which has a deflocculating effect on the cement particles, and allows them to flow more easily. In addition, the introduction of fly ash into cement can retard hydration, thus reducing the amount of hydration products formed, which could enhance or prolong consistence (Taylor 1997). The continuous decrease in consistence with increasing SDW contents may be attributed, therefore, to the presence of gypsum. The SDW contains 15% gypsum, which in normal cements is used to regulate setting and avoid flash setting of the clinker minerals. However, in binders with high gypsum contents, a rapid setting and subsequent hardening occurs as in gypsum plasters (Karni and Karni 1995, Kovler 1998). This may explain the reduction in consistence with the increase in gypsum content.

4.2. Strength

The effect of SDW content on the retardation of C-SDW and C-S-SDW concretes was more apparent in the compressive strength data. Strength provides an indirect measurement of the rate and degree of hydration. The replacement of cement with SDW resulted in a loss of strength during the first 28 days compared to the reference mix. An increase in the SDW content increased the strength reduction during this period. After seven days, all mixes show an increase in relative strength with age, the rate of increase was higher in lower SDW content mixes. C-SDW concretes containing 10% and 20% SDW exhibit a compressive strength greater than the reference mix. The optimum SDW content was 10%, which gave the maximum relative strength of 120% at 365 days. However, all C-S-SDW mixes showed systematic reduction in strength with the increase in SDW content.

Replacing cement with SDW in concrete has a retarding effect on strength. This retardation increased as the level of SDW in the concrete increased. The SDW composition was 85% fly ash and 15% gypsum both of which have retarding effects on the hydration of cement (Lea 1998; Wild et al 1995)**.** Gypsum is generally introduced to regulate the setting of cement, or more specifically the hydration of the C_3A component, in addition, fly ash retards the hydration of clinker minerals such as C_3S and C_3A (Fajun et al 1985). The CH, which is commonly supplied by cement, reacts with the silica and alumina parts of the fly ash to form additional calcium silicate and aluminate hydrates (C-S-H, C-A-H). However, compared to Portland cement, the reaction of fly ash is relatively slow (Khatib and Mangat, 1995; Khatib and Mangat, 2002). An increase in the SDW content, increased the proportion of fly ash in the mix, therefore, reducing the reaction rates (Khatib, 2008). Hence, the early strength development of fly ash cements is retarded. This would explain the reduction in early strength as the SDW in the C-SDW content was increased.

The blending of gypsum and fly ash in C-SDW concretes may also improve strength compared to normal fly ash concretes based on evidence from tests on pastes and mortars in which blending fly ash and gypsum did result in higher long-term strengths than fly ash alone (Poon et al 2001). The aluminate phase of the fly ash reacts with the sulphate ions, which breaks down the glassy and crystalline phases of the fly ash (Uchikawa, 1986). The addition of gypsum was shown to accelerate the reaction of fly ash with calcium hydroxide (CH) supplied by the cement, and strengthen the bond between the fly ash grains and the hydrates around them. Increasing the gypsum content beyond the optimum amount tends to reduce early strength but considerably increases long-term strength (Shiyuan 1982).

For the C-S-SDW concretes, strength development was greatly retarded compared to the reference mix. Even at 365 days, the relative strength of the C-S-SDW concrete ranged between 35% and 50% of the reference. The reduction in strength may be attributed to the reduction in alkali to allow the slag and the SDW to react. The use of slag usually requires some form of alkali activator such as CH, which reacts with its glassy parts to form C-S-H (Neville 2011). The contribution to strength usually occurs between 7 and 90 days depending on the slag content. Optimum cement replacement levels of slag, for maximising strength, lies between 40 to 50% (Roy and Idorn, 1982; Khatib and Hibberd, 2005). Improvements in strength for mixes containing up to 40% slag is commonly attributed to changes in the microstructure of the cement matrix. In slag cements, the amount of calcium hydroxide (CH) formed is reduced, and additional calcium silicate hydrates (C-S-H) are formed, which produce a much denser microstructure (Neville 2011). Slag content exceeding 50% reduce strength due to a lack of calcium hydroxide (CH), which reacts with the slag. The C-S-SDW concretes contain 10% cement, which was insufficient to produce strength similar to the reference mix. When cured in water the C-S-SDW concretes possessed a much more durable structure and damage to the samples was less common. The C-S-SDW concrete containing no SDW, (mix $10_C90_S0_{SDW}$), exhibit an increase in strength after 28 days compared to the remaining C-S-SDW concretes. This is because slag possesses hydraulic properties and was more reactive than the fly ash present in the SDW (Concrete Society 2011).

4.3. Length change

The replacement of cement with fly ash generally has little effect on the drying shrinkage of fly ash concretes compared to reference concretes (Baoju et al 2000). Drying shrinkage for fly ash concrete lies between 500µs and 600µs at 365 days, which is also common for normal concretes. However, an increase in the SDW content in C-SDW concretes resulted in a decrease in the drying shrinkage.

Figure 10 shows the relationship between drying shrinkage and compressive strength of cubes cured in water at different curing times. The relationship suggests that an increase in compressive strength leads to an increase in drying shrinkage. This indicates that drying shrinkage is related to the degree of hydration. A decrease in hydration will reduce the surface area of the gel formed, and would reduce the adsorbed water on the surface of the gel particles, thus minimising the shrinkage on drying. In addition, drying shrinkage occurs from the removal of intracrystalline water from the C-S-H (Neville 2011). Therefore, a reduction in the C-S-H formed due to the retardation of the hydration process may contribute to the reduction in drying shrinkage.

The drying shrinkage of C-S-SDW concretes follows no apparent trend with respect to SDW content and varied between 250µs and 500µs at 365 days. Hogan and Meusel (1981) reported that the drying shrinkage of concrete containing 50% slag generally increased at all ages compared to normal concretes. However, the presence of slag in the C-S-SDW concretes does not lead to any significant drying shrinkage. It was suggested that the shrinkage could be reduced with the addition of gypsum. This may explain why the C-S-SDW concretes all exhibit a drying shrinkage similar to or less than the reference mix. All C-S-SDW concretes possess lower compressive strengths than the reference mix, however, the drying shrinkage of several C-S-SDW concretes was similar to the reference mix. Therefore, it is more likely that the drying shrinkage is governed by the physical properties of the binder materials such as fineness, water reducing properties or even the type of hydrates formed during hydration.

The expansion of C-SDW concretes cured in water exhibited the opposite trend to drying shrinkage, i.e. an increase in the SDW content, increased the expansion in the C-SDW mixes. The increase in expansion with increasing SDW content was accompanied by a retardation of strength. Expansion appeared to cease in C-SDW concretes once the compressive strength reached approximately 15N/mm^2. For the reference mix, this occurred between one and three days, whereas, for the mix containing 70% SDW (mix 30_C70_{SDW}) this occurred between 28 and 90 days. The expansion of C-S-SDW concretes follows no particular trend with respect to SDW content. The only significant observation was that C-S-SDW concretes, which exhibit a large drying shrinkage, also exhibit small expansion. In mixes containing 10% SDW ($10_C80_S10_{SDW}$) and 40% SDW ($10_C50_S40_{SDW}$) there was an initial shrinkage followed by a small expansion with time.

Increasing the SDW content increased the gypsum content in the mix, which can influence expansive properties of concrete (Pickett 1947). Lerch (1946) reported that in normal cements and under moist curing conditions, minimal expansions were observed at SO_3 contents up to 4%. Many researchers have reported results on why calcium sulphate and the ratio of SO_3/Al_2O_3 cause expansions in cement (Sorka and Abayneh 1986; Mulongo and Ekolu 2013). However, many views are contradictory. The consensus is that large amounts of gypsum in the mix can result in excessive ettringite formation, and subsequent expansions.

5. Conclusions

Physical and mechanical properties were tested on concrete with proportions of binder to sand to coarse aggregate of 1:2:3.5, and a water/binder (w/b) of 0.5. The influence of cement replacement level with a typical simulated desulphurised waste (SDW) was evaluated for binders containing cement and SDW (C-SDW blends), and cement, ground granulated blastfurnace slag and SDW (C-S-SDW blends). There is a potential to use desulphurised wastes in construction applications provided the limitations of the materials are recognised.

The replacement of cement with increasing levels of SDW beyond 10% generally reduced compressive strength, drying shrinkage and increased water absorption and expansion.

The drying shrinkage of C-SDW concrete appeared to be related to the degree of hydration and strength. Increasing the SDW content retards strength, which coincided with a decrease in drying shrinkage for samples cured in air. All C-SDW concretes exhibited a drying shrinkage lower than the reference concrete. For example, the reference mix exhibited a drying shrinkage of 500µs, however, an increase in the SDW content up to 70% decreased drying shrinkage to 150µs.

The expansion of C-SDW concretes appeared to be inversely related to drying shrinkage, i.e. an increase in drying shrinkage was accompanied by a decrease in expansion. An increase in expansion occurred when the level of SDW was increased. For example, the reference mix exhibited no expansion, however, an increase in the SDW content up to 70% increased the expansion to 1100µs.

The performance of all C-S-SDW concrete was inferior to the reference concrete. Generally, compressive strength, drying shrinkage were decreased, and water absorption and expansion were increased. However, if sufficient curing was provided it was possible to produce concrete with waste contents as high as 90% (slag and SDW). For example, the strength of all C-S-SDW concretes was approximately 35 N/mm² at 365 days, compared to 67 N/mm² for the reference concrete.

There appears to be a relationship between drying shrinkage and expansion, i.e. large expansions were observed for mixes that exhibited small drying shrinkage. The expansion of C-S-SDW concretes was less than the expansion exhibited by the C-SDW concretes with equivalent SDW contents. For example, C-S-SDW concrete containing 70% SDW exhibited an expansion of 500µs, whereas the C-SDW concrete containing the same level of SDW exhibited an expansion of 1100µs after 570 days.

6. Recommendations for practical mix design

The research reported in this paper was part of a larger project funded by the EC, on FGD waste produced by the semi-dry and dry desulphurisation processes used in Eastern Europe. The variability of the FGD ashes produced by different power stations was significant and, therefore, mix design can only be based on any specific selected source. Chemical characterisation and grading of these FGD ashes would be the first step leading towards their application. 10 – 15% replacement of cement with FGD waste in plain concrete mixes would be a suitable mix design for products without steel reinforcement. Durability of steel reinforcement in the material needs to be verified before its use in reinforced concrete.

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Table 1: Binder details for C-SDW mixes

		Proportions (% mass of binder)		SO_3
Mix No	Mix ID	Cement (C)	SDW	(% mass of binder)
1	REF (100_C)	100	0	3.12
2	90_C10_{SDW}	90	10	3.70
3	80_C20_{SDW}	80	20	4.27
4	70_C30_{SDW}	70	30	4.85
5	60_C40_{SDW}	60	40	5.42
6	30_C70_{SDW}	30	70	7.15
7	10_C90_{SDW}	10	90	8.30

Table 2: Binder details for C-S-SDW mixes

		Proportions (% weight of binder)			SO_3
Mix No	Mix ID	Cement (C)	SDW	Slag (S)	(% mass of binder)
8	$10_C90_S0_{SDW}$	10	0	90	1.06
9	$10_C80_S10_{SDW}$	10	10	80	1.86
10	$10_C70_S20_{SDW}$	10	20	70	2.67
11	$10_C60_S30_{SDW}$	10	30	60	3.47
12	$10_C50_S40_{SDW}$	10	40	50	4.28
13	$10_C20_S70_{SDW}$	10	70	20	6.69

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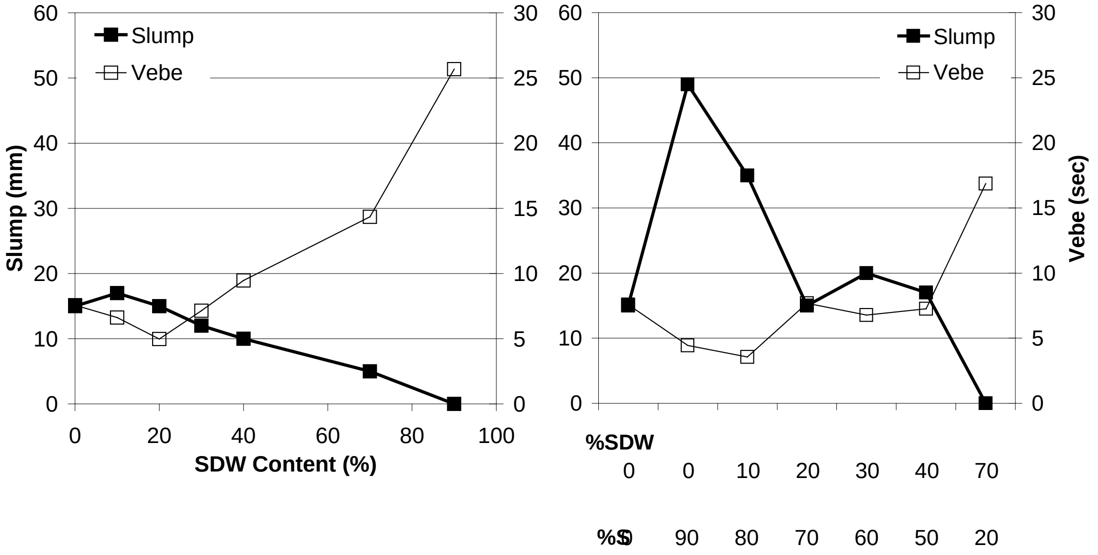
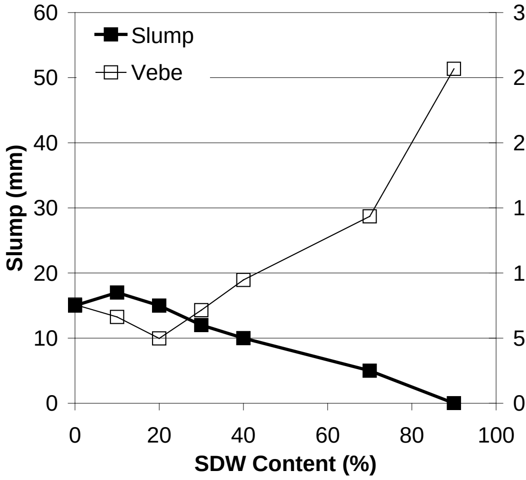


Figure 1. Workability of (a) C-SDW and (b) C-S-SDW Concretes



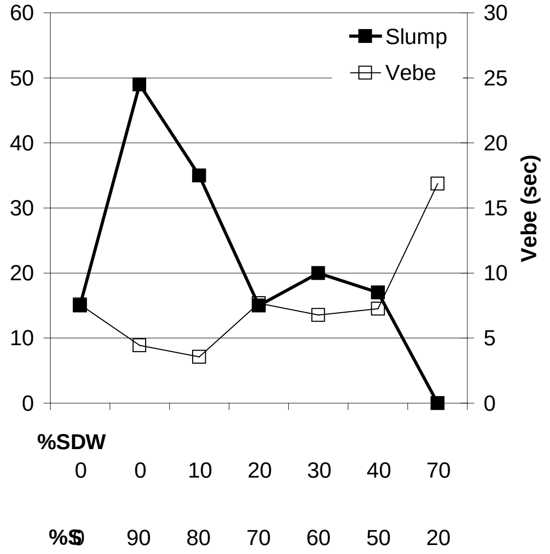


Figure 1. Workability of C-SDW Concretes

Figure 2. Workability of C-S-SDW Concretes

Figure 1. Workability of (a) C-SDW and (b) C-S-SDW Concretes

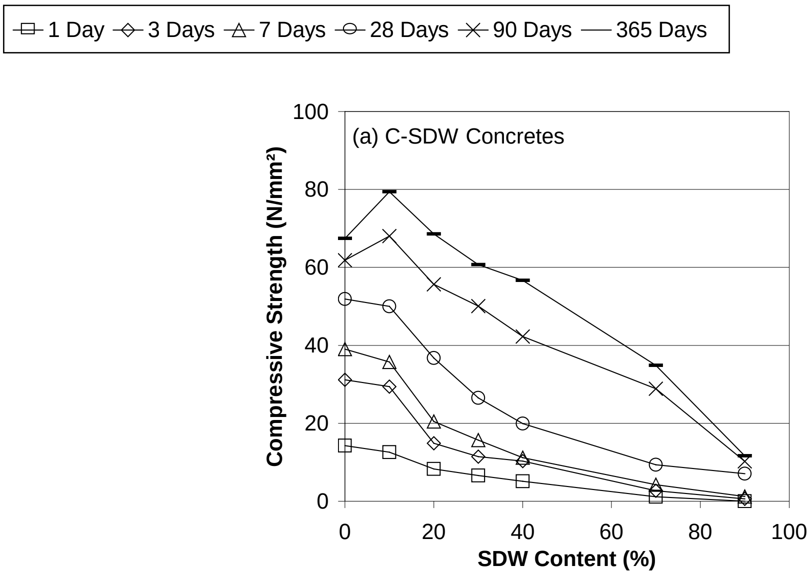


Figure 2: Influence of SDW content on compressive strength at different curing times.

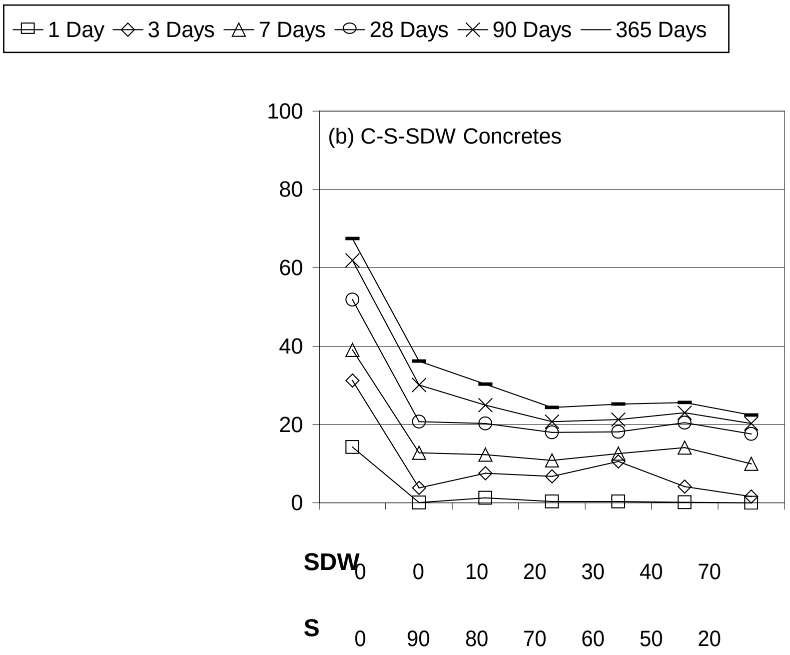


Figure 3: Influence of SDW and S contents on compressive strength at different curing times.

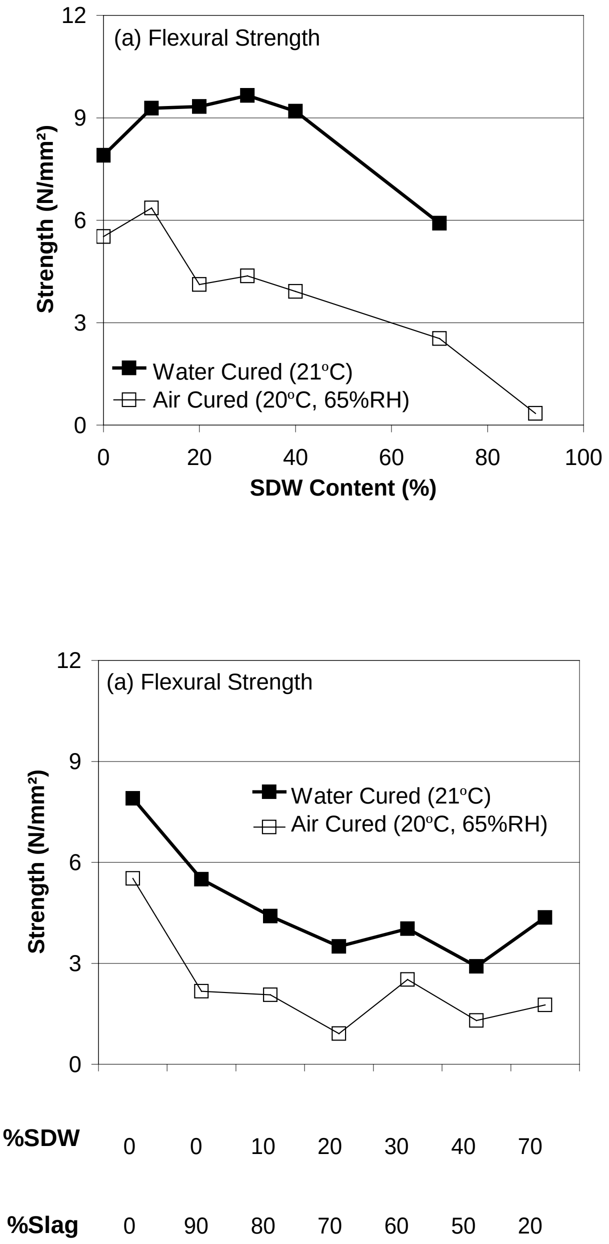


Figure 4: Influence of SDW content on the flexural strength of (a) C-SDW and (b) C-S-SDW concretes

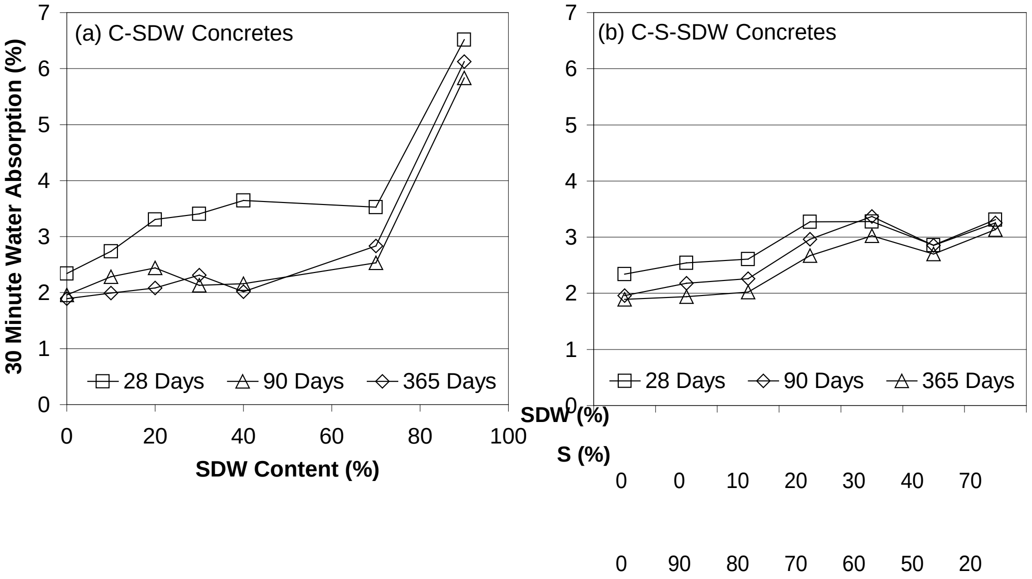


Figure 5: Water absorption of (a) C-SDW and (b) C-S-SDW concretes

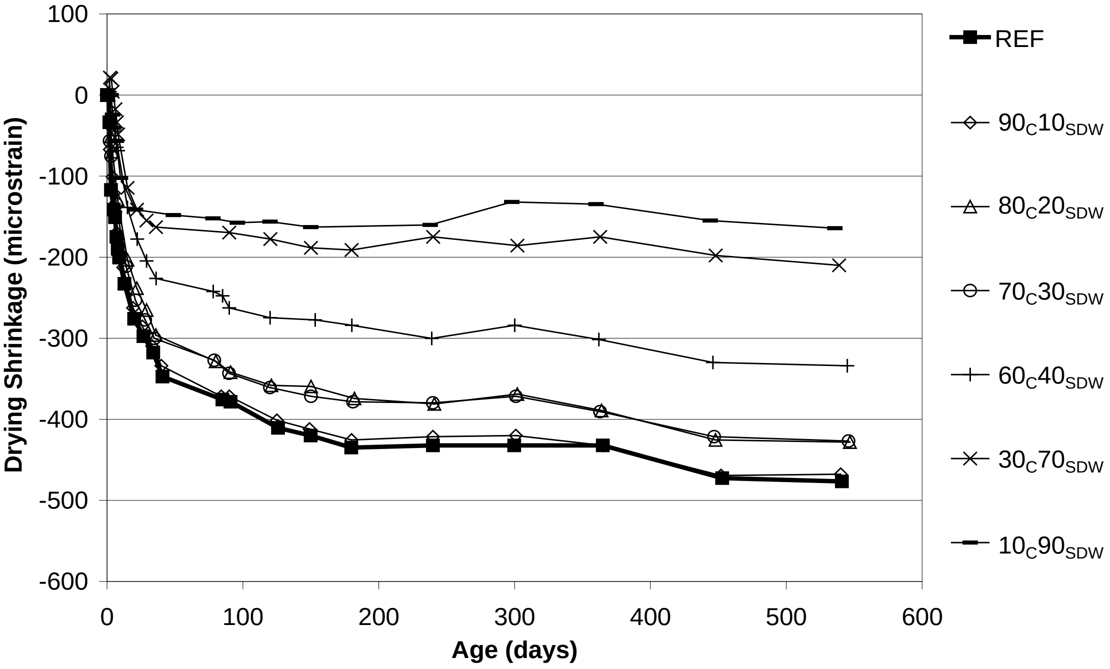


Figure 6: Change in drying shrinkage with time for C-SDW concretes

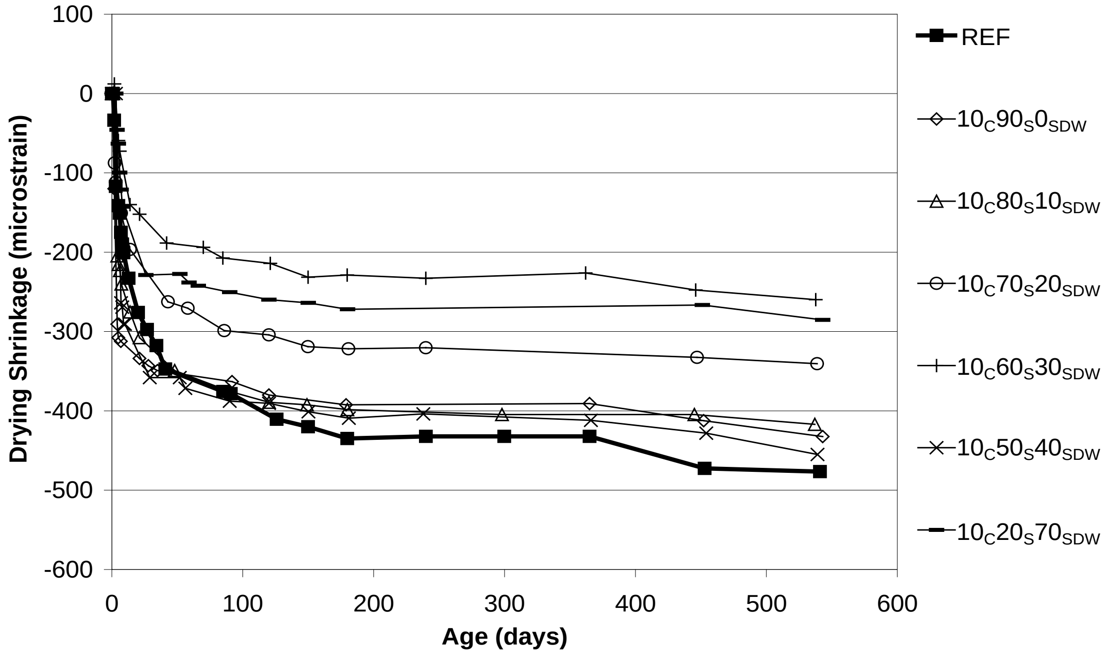


Figure 7: Change in drying shrinkage with time for C-S-SDW concretes

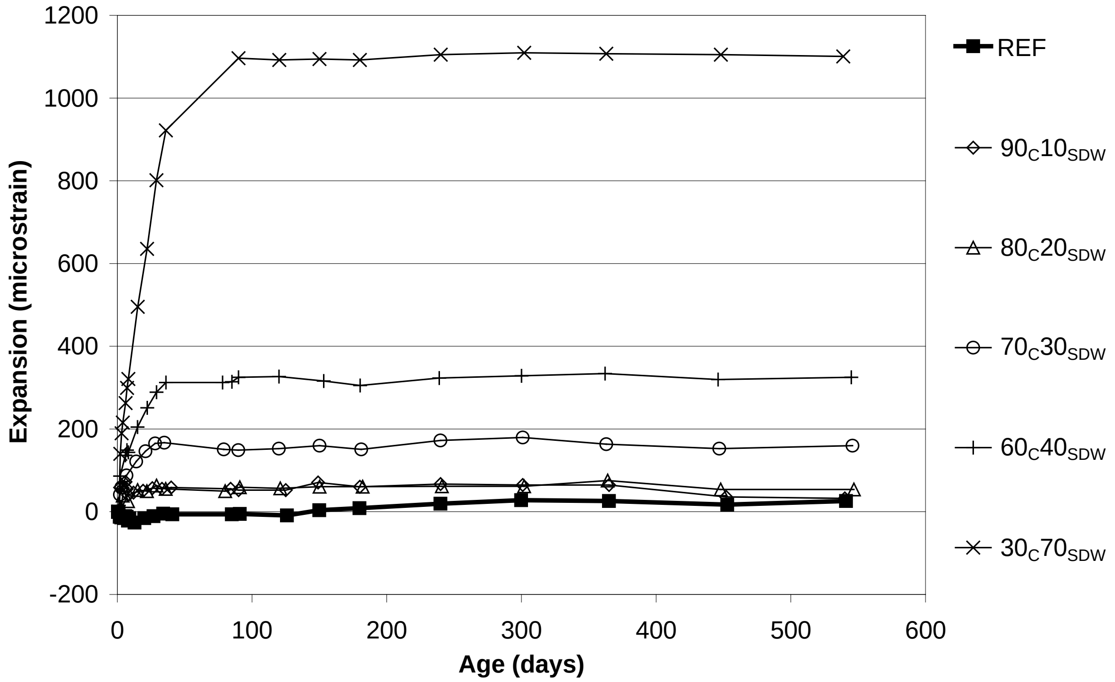


Figure 8: Influence of age on the expansion of C-SDW concretes

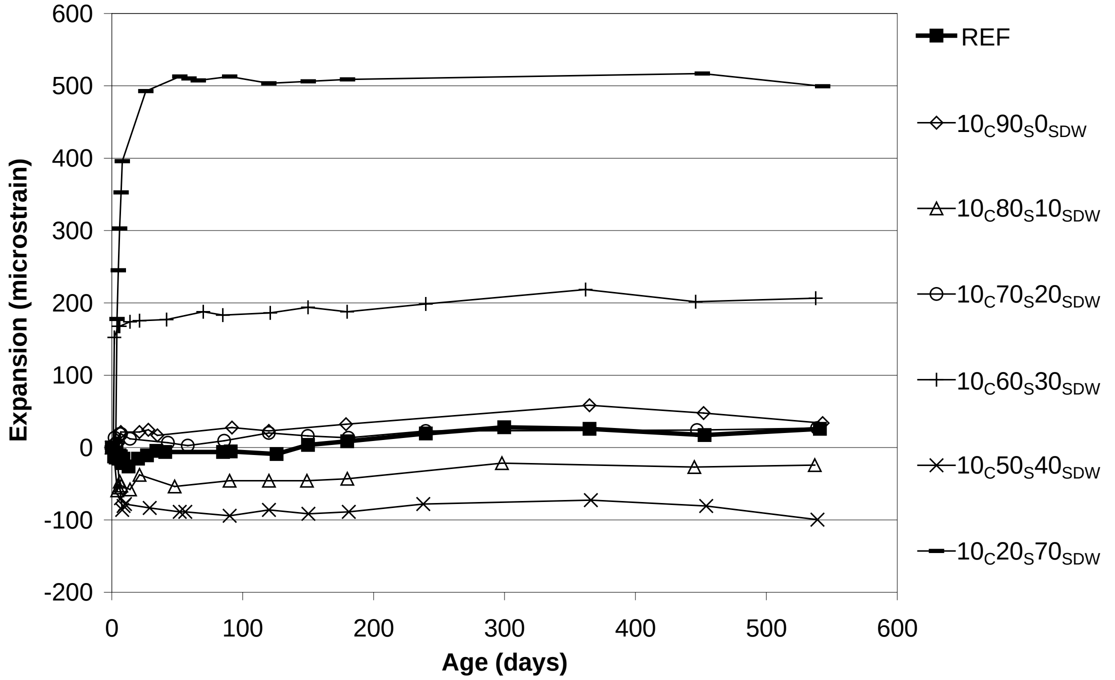


Figure 9: Influence of age on the expansion of C-S-SDW concretes

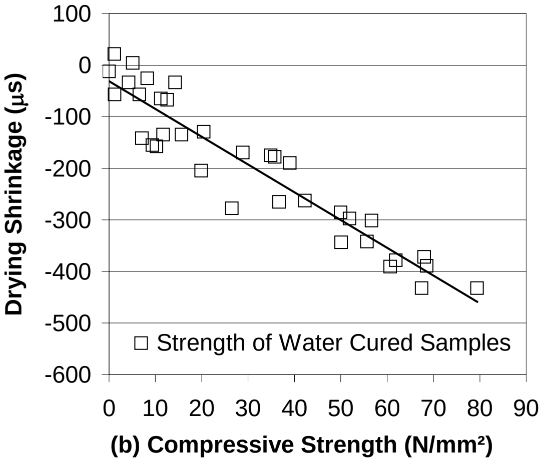


Figure 10: Relationship between drying shrinkage and strength of C-SDW concretes