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MYRIAD SEGMENTS

10,000 carbon-conscious, fibre-reinforced precast units for Silvertown Tunnel

EVALUATING CONDITION AND FORM

Guidance on the approach to surveying and testing hardened concrete

RESEARCH AND DEVELOPMENT

Looking at the latest efforts to improve the carbon performance of concrete

LEFT:
Figure 1 – the set-up for monitoring compressive creep of concretes.

TOP RIGHT:
Figure 2a – shrinkage of concrete specimens. Note, dash-dot represent specimens exposed sealed conditions and the solid lines unsealed.

FAR RIGHT, TOP:
Figure 2b – specific creep of investigated concretes. Note, drying shrinkage strain was excluded from the creep strain.

BOTTOM RIGHT:
Figure 3 – embodied carbon associated with the investigated concrete and their sources (a) without accounting for steel reinforcement and (b) with steel reinforcement.

Low-carbon concreting: a harmonised approach between material selection and design

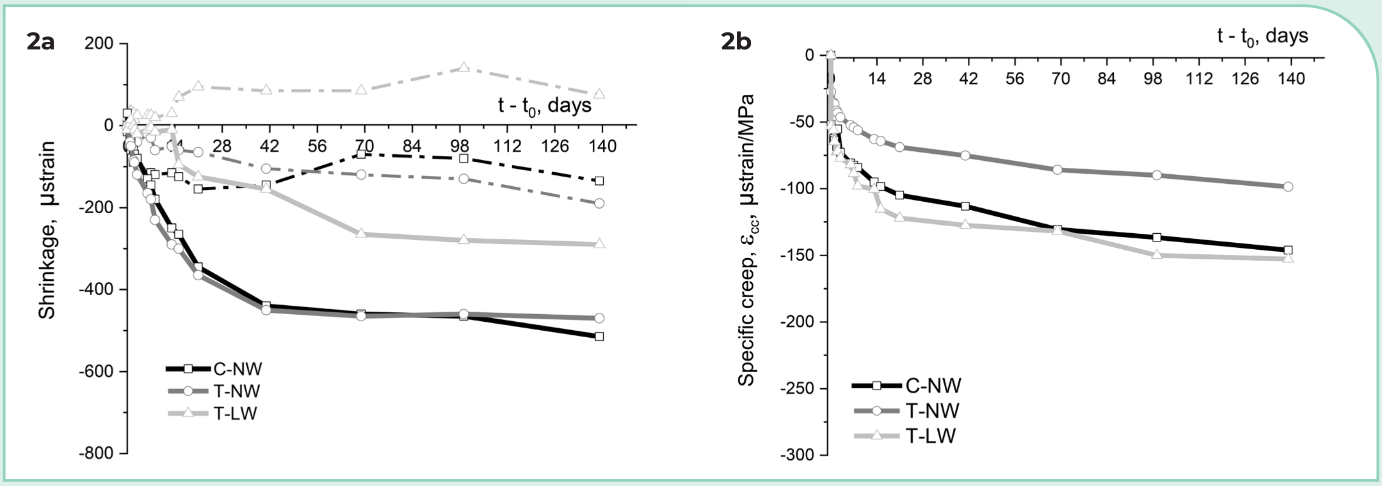
With increasing pressure to reduce its carbon footprint, the concrete industry is already adopting cements with lower clinker factors, eg, CEM VI. However, practical limits around high Portland cement substitution (ie, slow strength development) and uncertainties around the availability of substituents, eg, fly ash and GGBS, warrant coupling of approaches if the industry is to meet its net-zero targets. **Sam Adu-Amankwah** of the **School of Civil Engineering** at the **University of Leeds** argues the case for low-carbon lightweight concreting, in which the benefits of clinker substitution are combined with lightweight structural elements.

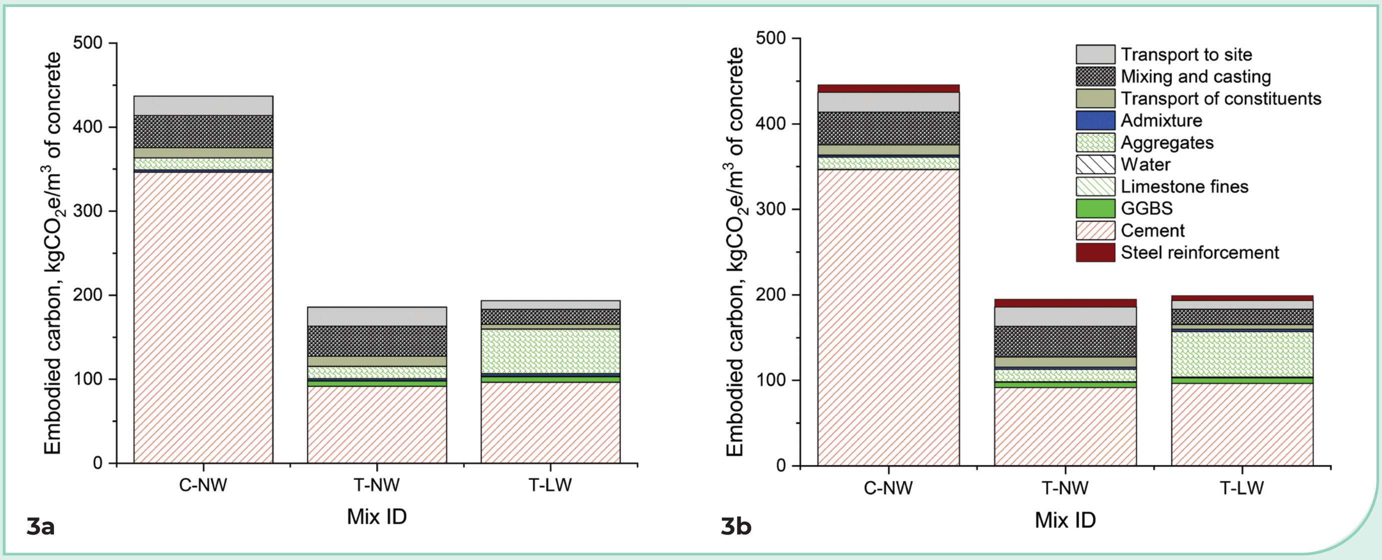
The long-term availability of cement substituents, eg, fly ash and GGBS is threatened by closure of coal-fired power stations and blast-furnace foundries. The recently introduced BS EN 197-5[1] permits combinations of up to 20% limestone with GGBS or fly ash and CEM I in the so-called ternary systems. This has potential to ease over-reliance on GGBS and fly ash. Ternary cements can reduce the embodied carbon from 0.178kgCO_2e/kg to less than 0.1kgCO_2e/kg for a typical C40/50 strength-class concrete. The challenge is, high clinker replacement reduces early strength development and hence its content cannot be lower than 50% for most structural applications. This places a limit on the extent to which carbon reductions can be realised through cement composition only.

Design efficiency can further reduce the CO_2e by optimising the quantities of concrete and steel reinforcement. This means designers specify appropriate materials in their required quantities for a given application. This can only be achieved if the concrete's composition-versus-function relationship is embraced by stakeholders. From a design viewpoint, compressive strength is perhaps the most critical functional requirement of structural concrete. Design parameters such as elastic modulus, creep and shrinkage, among others, may be derived from this. However, lightweight and normal-weight concrete options exist for most strength requirements, eg, LC45/50 versus C40/45 strength class. The structural designer's default seems to be normal-weight concrete in most cases. Evidencing potential CO_2e savings may incentivise widespread uptake of lightweight concrete. The objective of this contribution is to present the mechanical properties of a low-carbon lightweight concrete and demonstrate its CO_2e reduction potential.

MATERIALS AND METHODS

Three concretes – plain CEM I 52,5 N (reference) and two limestone ternary blended cement concretes, as detailed in Table 1, were investigated. The ternary cements were prepared by partial substitution of CEM I 52,5 N, with 40% GGBS and 10% limestone. The reference was prepared





with normal-weight aggregates (designated C-NW), while the limestone ternary cement concrete had either normal-weight aggregate (T-NW) or manufactured Lytag aggregates (T-LW). The normal-weight aggregates were uncrushed quartzite, while the Lytag conformed to BS EN 13055[2]. The fine and coarse Lytag had 4mm and 14mm maximum sizes with 1050 and 740kg/m^3 densities respectively. Moisture uptake by the aggregates, especially the Lytag, can present consistence problems. Therefore, the aggregates were presoaked and surface dried before mixing. A PCE-based plasticiser at 0.3% by weight of the binder was used. The w/b ratio was maintained at 0.25 in all concretes.

The concrete samples were prepared according to EN 12390:2[3] using a planetary mixer. After mixing, fresh properties including flow diameter, air content by the pressure method and density were measured before casting. Specimens were cast for compressive and tensile strength, elastic modulus, drying shrinkage and compressive creep testing.

The moulds were kept under moist hessian for one day, after which they were demoulded and stored in a 99% relative humidity room until testing.

Compressive testing was performed on 100mm cubes, while bobbin-shaped specimens were used for direct tensile testing and hence determination of the elastic modulus. For the latter, the samples were instrumented with surface-mounted strain gauges and tested on an Instron universal testing machine. The strains and loads were logged at incremental load steps and the elastic modulus was calculated as the slope of the load deformation plot up to 40% of the failure load. Drying shrinkage and compressive creep were measured on 75 × 75 × 200mm prisms after seven-day moist curing. The lateral sides to the cast surfaces were instrumented with demountable mechanical (DEMEC) points following the methodology of BS EN 12390-17[4] and creep measured under controlled conditions of 30% stress:strength ratio, 65% relative humidity and 20°C temperature for up to 150 days.

RESULTS AND DISCUSSION

FRESH AND HARDENED PROPERTIES

Fresh properties of the investigated concrete are shown in Table 1. The normal-weight concretes were less workable, conforming to flow class F3, while the Lytag ternary cement concrete conformed to class F5. The air contents of the normal-weight fresh concrete were comparable regardless of cement type but significantly higher in the lightweight concrete. These trends were expected due to fineness of GGBS, densities of the aggregates and additional porosity in the Lytag, compared with the uncrushed quartzite aggregates.

Hardened properties of the concretes monitored up to 150 days are presented in Table 2. The aggregate type was the main factor controlling the concretes' air-dried density. That of the Lytag ternary cement concrete conformed to class D1.4, while the normal-weight concretes were ~2350kg/m^3. The seven-day compressive strength exceeded 45MPa in the CEM I mix but the ternary cement was around

Mix ID	Binder, kg/m³	Fine aggregate, kg/m³	Coarse aggregate, kg/m³	w/c	HWRA, l/m³	Flow diameter, mm	Fresh density, kg/m³	Air vol, %
C-NW	380	692	1264	0.25	1.2	480	2435	0.9
T-NW	380	689	1256	0.25	1.2	440	2345	1.3
T-LW	400	272	356	0.25	1.5	610	1445	4.2

Mix ID	Air dried density, kg/m³	Compressive strength, MPa			28d tensile strength, MPa	Elastic modulus, GPa
		7-day	28-day	150-day		
C-NW	2350 ±20	46.8 ±2.5	54.8 ±1.8	58.8 ±2.5	2.1	23.1
T-NW	2330 ±20	31.2 ±2.3	59.3 ±2.8	65.3 ±1.8	1.8	22.7
T-LW	1370 ±15	33.8 ±1.6	63.0 ±2.3	73.1 ±3.0	3.1	25.8

ABOVE:
Table 1 – mix design of investigated concrete (kg/m³).

LEFT:
Table 2 – mechanical properties of investigated concrete.

BELOW:
Table 3 – CO_2e of the constituent materials ($kgCO_2e/kg$) used.

Constituent	CEM I	GGBS	Limestone	Gypsum	Plasticiser	Natural aggregates	Lytag aggregates	Steel
$kgCO_2e/kg$	0.083	0.0416	0.0158	0.0025	1.88	0.007	0.085	0.73

Matric/mix ID	Without steel			With steel		
	C-NW	T-NW	T-LW	C-NW	T-NW	T-LW
$kgCO_2e/m^3$	437	186	193	446	195	199
$kgCO_2e/kg$	0.18	0.08	0.17	0.18	0.08	0.18
$kgCO_2e/MPa$	7.97	3.13	3.07	8.14	3.29	3.18
$kgCO_2e/GPa$	18.91	8.19	7.49	19.30	8.59	7.76

LEFT:
Table 4 – embodied carbon per function unit of concrete.

30MPa. However, contribution of the GGBS hydration was evident from the 28- and 150-day compressive strength, reaching about 60MPa after 28 days. Interestingly, after 150 days, the Lytag ternary cement concrete outperformed the normal-weight mix by about 8MPa. The brittleness of Lytag notwithstanding, its direct tensile strength and elastic modulus exceeded the two normal-weight concretes, plausibly due to the higher compressive and tensile strength of the matrix. These observations can be explained in terms of the additional binder content (ie, extra 20kg/m³) as well as internal curing provided by the Lytag.

Dimensional stability of the concrete is another important design consideration. These were measured on seven-day moist cured sealed and unsealed specimens, while compressive creep was measured on unsealed specimens at 30% stress:strength ratio. As shown in Figure 2a, in the sealed specimens, the Lytag concrete rather expanded, while the normal-weight concrete shrank as noticed elsewhere[5,6]. The moderate expansion is indicative of internal curing leading to more hydration products or moisture suction by the reaction products from the Lytag. In the investigated time range, drying shrinkage strain was smaller in the Lytag than both normal-weight concretes. Similar observations were made in Zhang and Paramasivam[7] but contradicts those in others[8,9]. The improved properties of the Lytag may be due to the expansion strain as explained above and the lower w/b ratio considered in the present study. Meanwhile, specific creep of the concretes in Figure 2b show reduction in creep strain per unit stress in the normal-weight limestone ternary cement mix. However, this increased to comparable ranges as the reference CEM I mix.

EMBODIED CARBON (CO_2e) REDUCTIONS

The above-presented mechanical properties show that Lytag ternary cement concrete can perform comparably or better than normal-weight concrete from the same cement or CEM I with respect to strength, elastic modulus and dimensional stability. These are significant from a design viewpoint because the lower self-weight can be exploited to achieve further savings in CO_2e. In the section that follows, such savings are discussed. The CO_2e of the constituent materials used for these calculations was taken from the ICE database[10] but that for Lytag was from Anderson and Moncaster[11] and is shown in Table 3. The case is presented for a single spanning category A floor slab. A superposition approach was used to calculate the carbon footprint of normal-weight CEM I, ternary cement and Lytag ternary cement concrete.

Figure 3a shows the CO_2e of the three concretes based on the choice of materials only. It is observed that over 50–60% saving in the CO_2e/m^3 of concrete can be achieved with the use of limestone ternary cement. This arises from 50% reduction in CEM I. For the limestone ternary cement, the CO_2e/m^3 was slightly higher with the Lytag than normal-weight concrete. This is due to the embodied carbon (42–85$kgCO_2e/t$) associated with Lytag production. Recent advances in lightweight aggregate production from industrial flue gas should culminate in further reduction or even carbon negative aggregates, which should reduce the CO_2e of lightweight concrete even further.

Additional to the above CO_2e savings, the Lytag concrete also reduce the design loads and hence reinforcement demand in concrete. The typical slab analysis, presented in the side panel to the right, shows that the 1m³ of Lytag concrete required 4T8 bars @250 c/c as opposed to 4T10@250c/c in the normal-weight concrete. This translates to 0.212kg/m saving in reinforcement and approximately 3.23kgCO_2e/m³ of concrete as shown in Figure 3b. The benefits become even clearer when the CO_2e is considered with functional units as presented in Table 3.

The CO_2e/m³ and CO_2e/kg alone do not present an accurate picture as argued in Purnell and Black[12]. The savings derived from specifying Lytag is noticeable per unit strength and elastic modulus, with or without steel reinforcement. The latter increases the CO_2e of concrete, which is not captured in most CO_2e calculations. It is demonstrated that the Lytag concrete has lower CO_2e per compressive strength and elastic modulus, which are critical design considerations.

CONCLUDING REMARKS

The mechanical properties of the concretes were comparable from 28 days. Designing with the lightweight concrete leads to reduction in the amount of steel required and saves on transport-related emissions. The Lytag ternary cement concrete shows better embodied CO_2 per unit strength and elastic modulus. Consequently, structural concrete designers and concrete suppliers have an option to couple sustainable cements with lightweight aggregates to produce concretes with a lower CO_2 footprint. C

Consider 1m³ of concrete in a single spanning slab that is to support 2kN/m² variable load. If the thickness is assumed to be 200mm, the cubic metre of concrete will fill 5 × 1m area (ie, 5 × 1 × 0.2). Based on a 5m span, comparison can be made for a choice between normal-weight and lightweight aggregate concrete. The design of such a slab, associated checks for adequacy and reinforcement required are presented below:

	Normal-weight concrete	**Lightweight concrete**
Mild steel, f_{yk} (MPa)	460	
f_{ck} (cube), MPa	55	60
f_{ck} (cm), MPa	45	55
Density kN/m³	24	14
Depth, mm	200	
Span, m	5	
Self-weight, g_k, kN/m²	4.8	2.8
Variable loading, q_k, kN/m²	2	2
Ultimate design load, F (kN)	47.4	33.9
Eff. depth, d. Assuming 20mm cover and 12mm bars	174	
Mid-span moment for interior single-span slab (kNm) = (0.07Fl)	16.59	11.865
Bending reinforcement		
(M/bd^2f_{ck})	1.21769E-08	7.12536E-09
Area of reinforcement required		
Lever arm, $z = l_a d$, $_{la}$=0.96	167.04	
As = $M/0.87f_{yk}z$ (mm²/m)	248.169737	177.4884828
Check 100As/bd	0.142626286	0.102004875
Span to eff. depth ratio	28.73563218 <41.7 √	28.73563218 <41.7 √
Required reinforcing bars (kg/m³)	4T10@250c/c (12.3)	4T8@250c/c (7.9)

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