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ARUP

VALUE OF SPECIAL CONCRETES IN STEEL FRAMED BUILDINGS

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SYNOPSIS

Tarmac commissioned Arup to investigate the value of using two Tarmac products; a high early strength gain concrete, brand name Toproc Rapid, and a self-compacting concrete, brand name Topflow.

The purpose of the study was to identify opportunities for design and construction savings in steel framed buildings using special concretes, Topflow (self-compacting concrete) and Toproc Rapid (high early strength concrete), and the overall benefits transferred to the stakeholders of the building.

Arup reviewed the potential design benefits of reduced rebar or member sizes, and also the associated labour and programme advantages. The review was undertaken at an element level of columns, RC slabs, walls and composite slabs; and also using real building case studies. Two case study buildings were considered; a 16 storey RC flat slab residential building and a 21 storey London City steel framed office building with RC cores and composite concrete slabs.

This report describes the findings of the steel framed building study. The results of the Concrete Building Study are summarised in a separate report available from Tarmac.

The case study buildings were selected from recent Arup projects to allow the use of factual information leading to a representative real-world and future project applicable outcome to the study. The design was then modified to take advantage of the properties of the special concrete mixes but the construction techniques such a core construction and floor construction cycles remained unchanged.

From the summary of cost savings shown in Table 5, it is evident that there are savings to be realised when using Toproc Rapid in shear cores and that Topflow self-compacting concrete (SCC) provides savings when used in composite slabs, due to its inherent speed of placing. This report explores these savings and a summary of the methodology and results follow.

The added value is realised at both the elemental and whole-building level. At the elemental level, value in the form of realisable cost reductions of up to 17% for shear cores and 5% for RC composite slabs. In order to realise these savings the high 28-day strength of Toproc Rapid needs to be considered during the design process to realise smaller elements. At the whole-building level, a concrete construction package cost reduction of 2% was found, with improved area metrics adding value equivalent to 1% of the concrete construction package.

The main regional focus of the study was the London market, but UK regional variations are also considered.

INTRODUCTION

Design and construction using conventional concrete for steel framed multi-storey and high rise building structures is a long established building method. Tarmac believes there is a step change opportunity for the construction industry to deliver value through adopting special (proprietary) concrete solutions. The traditional approach to developing concept designs, then following the various procurement methods: detailed design, main and sub-contractor appointments, results in innovation in readymix concrete to deliver an efficient building system being overlooked. The challenge was to identify how and where the key players: building owners, structural designers and building contractors could realise commercial benefits and / or design efficiencies.

Tarmac engaged Arup to independently investigate whether using special concrete delivers a more efficient building solution, to benefit main contractors and building owners throughout the UK from both structural design and building construction perspectives.
The scope of Arup's study is limited to the superstructure: substructure and ground floor slab construction is excluded. The study does not consider the respective merits of insitu concrete or steel framed building structures per se, but challenges the status quo default to conventional concrete, to identify where concrete innovation can add value in both types of construction.

Arup's investigation commenced at an elemental level (composite slabs and shear cores) to seek to identify opportunities for design and construction savings in using Topflow (self-compacting concrete) or Toproc Rapid (high early strength concrete) as the build method for individual structural elements. Elemental benefits, such as thinner walled shear cores and quicker floor construction were examined from both design and commercial perspectives (including accelerated build, increasing lettable floor areas.)

The findings of the element study were then scaled up and incorporated in an assessment of the overall build of the structural frame to identify high level benefits for the project in using Topflow and Toproc Rapid concretes. This was based on a real case study building in the City of London and covered aspects such as optimising shutter utilisation, effectively at sub-contractor level, through to reducing the build time for the complete structural frame: the corresponding impact on the overall build programme and cost savings on preliminaries, and potential for earlier release of the completed building to the building owner for subsequent sales / lettings.

OVERVIEW OF SPECIAL CONCRETE MIXES CONSIDERED

Toproc Rapid is a proprietary high early strength and high 28 day strength concrete, with mixes typically tailored to achieve 35/40MPa at 24/48hrs respectively. Other higher early strengths can be achieved to suit other construction requirements but they are not part of this study.

Topflow is a proprietary free flowing self-compacting concrete that is designed to flow easily through highly congested, heavily reinforced areas and locations with difficult access. Topflow concrete is suited for precast and insitu concrete applications including reinforced concrete and steel framed building structures and can be designed to achieve high early and 28 day strengths.

For the purpose of this study, Topflow was assumed to have the same design properties as a standard C30/37 concrete, so there were no design benefits to be realised when compared to a conventional concrete. However, based on data obtained from the industry, Topflow can typically be placed using one third of the labour and a quarter of the time of conventional concrete in most situations, which delivers programme savings.

The intention of this study is to assess the benefits of Topflow in terms of speed of construction. It is important to recognise the versatility of Topflow; it has been supplied with low heat, high strength and high early strength properties as well as using steel fibres.

STUDY METHODOLOGY: ELEMENT STUDY

The element study considered the design of principal structural elements for office and residential loading. For each element studied, a typical 'base case element' was selected to establish a standard design benchmark for that particular type of element: in effect establishing a benchmark for the study. Each base case element was then used to investigate cost, design and programme benefits realised from the use of special concretes. Overall programme savings to the main contractor's construction programme, are not considered in the element study. This was subsequently considered in a whole building study.

To estimate cost savings, a technical study and build programme was developed for each element. This provided the basis for the cost modelling with the technical study informing the material requirements and the programme informing the labour requirements. Each element was then examined using special concrete mixes to identify potential material savings and consequent programme savings (from placing less material). Construction methodology was also reviewed to identify programme savings. For cost modelling: material rates were established using industry cost indices. This was used to inform the material, plant and labour costs. The overall cost for each element was checked against costs from other schemes as a method of ensuring the cost model data was within the range expected for each element. The elemental costs derived from the modelling were within the benchmarked data parameters.

Design benefits which make use of Toproc Rapid's high 28 day strength were investigated by considering either reducing the element cross section or reducing reinforcement quantities. These were then compared to the base case to evaluate material savings and increased floor space. To allow meaningful comparisons to be made, costs were calculated for four scenarios:

- Base case: conventional C30/37 concrete
- Programme only savings: using Topflow and Toproc Rapid as a straight substitution for standard mix
- Programme & design savings (reduced reinforcement and no change to element size): Toproc Rapid
- Programme & design savings (reduced member size and no change to reinforcement): Toproc Rapid

SHEAR WALLS

Shear cores were designed using Oasys AdSec to calculate section capacity charts (axial force vs moment capacity). These were then modified to account for buckling in line with EC2 section 5.8.7 using the moment magnification factor. For the purposes of the element study comparisons a U-shaped 'base case shear wall' was defined, as shown in Figure 1.

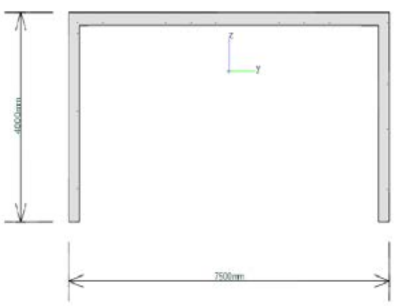


FIGURE 1

Shear core base case - C30/37
250 thick & H16s@300crs

The base reinforcement is assumed as H16s @ 300. A sensitivity study showed that the load capacity is sensitive to the unrestrained height of the wall (from floor to soffit above), and hence both office (4.3m unrestrained height) and residential (3.3m unrestrained height) heights were considered in the study.

Two base case wall thicknesses were investigated, 300mm and 250mm, to show the impact on buckling and any material savings. Cores were re-designed using Toproc Rapid, giving either reduced reinforcement or reduced wall thickness. Cost variations were assessed considering steel bar fixing, shuttering cycle times, concrete placing and curing for jump-form construction.

RC COMPOSITE SLABS

The slabs were designed for office and residential loading using Tata Steel's proprietary ComFlor software to EC2 and the effect on composite action with steel beams was investigated using Oasys Compos.

Due to the limitations of the ComFlor software, it was not possible to model concrete with a higher strength than C45/55.

However, the strength of the concrete was not a governing condition and hence this underestimation of Toproc Rapid's strength has no significant impact on the findings of this study. The increased stiffness of Toproc Rapid was modelled correctly

A 'base case composite slab' was defined as 130mm thick normal-weight concrete using ComFlor 60 as the decking, which is a standard starting point for designing composite floors, as shown in Figure 2. The span of this decking was then selected to utilise the deck as close to 1 as possible.

Unpropped slabs are governed by the construction deflection condition when the concrete is wet, and hence the metal deck governs the design. Hence a high early strength concrete with mesh or fibre reinforcement does not provide design benefits to composite floors.

In the case of propped slabs, these are governed by final deflection, and the higher stiffness of Toproc Rapid provides a small benefit. Greater benefit can be achieved through early de-propping, made possible by Toproc Rapid's high early strength but this was not explored further in this study and no cost savings were calculated. The effect of Toproc Rapid on the design of supporting composite beams was also investigated.

COMPARISON OF TOPFLOW AND LIGHTWEIGHT AGGREGATE COMPOSITE SLABS

A study was undertaken to demonstrate the effect in footfall induced vibrations when using lightweight concrete and the cost impacts of improving the floor response in other ways. A simple 7.5m x 10.5m grid with two slab spans per bay was created, as shown in Figure 3. A total of 4 by 3 bays were modelled to include the effect of multiple bays, and boundary conditions provided as appropriate to restrain the structure laterally.

Office loading was applied to the structure, and the material properties and support conditions were modified as appropriate for a dynamic analysis, using normal weight concrete to establish steel beam sizes, for a limiting response factor of 8 in accordance with SCI Guide P354. The design was then checked using lightweight concrete and the design adjusted to achieve the target response factor. Footfall analysis results are shown in Table 1.

Lightweight concretes are expected to give higher response factors than normal weight concrete. The dynamic response of the lightweight concrete was significantly worse than the normal weight Topflow concrete, with an unacceptable high response factor of 13.8.

To achieve an equivalent dynamic performance, it was necessary to add an extra secondary beam to each bay, potentially leading to increased piece-count and overall tonnage, as summarised in Table 1 and Figure 4.

It should be noted that the span and beam sizes were selected to ensure that the Topflow design had a just acceptable response factor, to demonstrate the most benefit of normal weight concretes. For shorter spanning slabs, or other conditions where the slab-beam system is stiffer, less benefit would be seen from higher mass in the slab, and a lightweight aggregate may perform acceptably without the need for additional steel.

FIGURE 2
Composite slab build up and support conditions

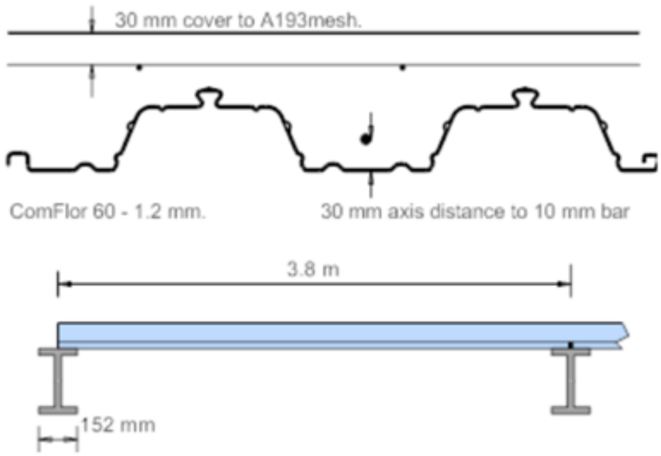


FIGURE 3
Footfall-induced vibration analysis model (Slab excluded from view for clarity)

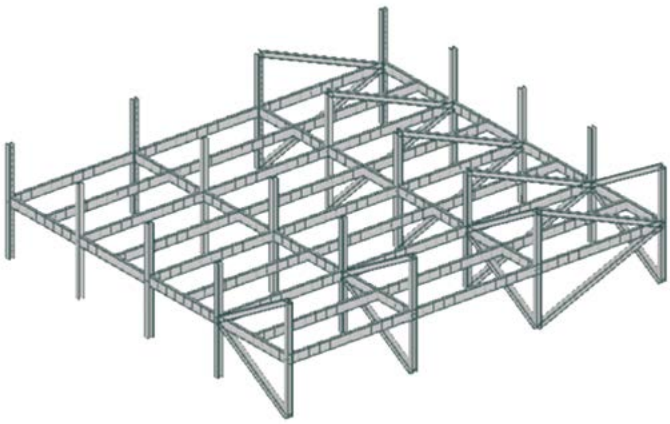


FIGURE 4
Breakdown of costs associated with Topflow and light weight concrete

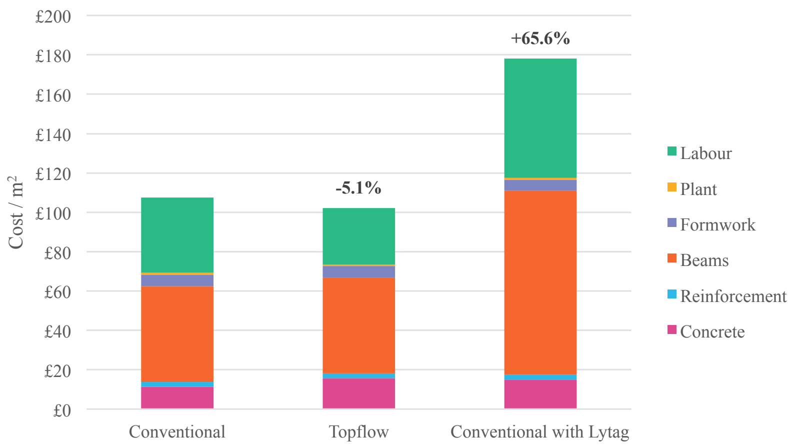


TABLE 1 Footfall induced vibration results

COLUMN	DECK	BAY SIZE (M)	SLAB TOTAL T (MM)	PRIMARY BEAM	SECONDARY BEAM	STEEL TONNAGE PER BAY	STEEL CHANGE	RESPONSE FACTOR
Topflow (normal weight)	Comflor 60mm 1.2mm thk	7.5x10.5	130	UB 686x254x125 (1 per bay)	UB 686x254x125 (2 per bay)	3.4	-	7,436
Lytag - unaltered	Comflor 60mm 1.2mm thk	7.5x10.5	130	UB 686x254x125 (1 per bay)	UB 686x254x125 (2 per bay)	3.4	0%	13.81
Lytag – extra, stiffer beams	Comflor 60mm 1.2mm thk	7.5x10.5	130	UB 838x292x176 (1 per bay)	UB 838x292x176 (3 per bay)	6.5	+91%	7,557

STUDY METHODOLOGY: BUILDING STUDY

A real building was selected to base a 'whole building' case study on, from a recent Arup project in the City of London, so it could use factual information for a representative real-world and future project applicable outcome to the study.

The design was then modified to take advantage of the properties of the special concrete mixes but the construction techniques such a core construction and floor construction cycles remained unchanged. The general arrangement and structural framing of each building were not reconsidered.

The programme for the building was then analysed to assess if the benefits identified in the element study could be realised in a complete building, and to what extent. Additional benefits of increased floor area due to smaller shear wall elements in the core were also assessed. These benefits were then translated to commercial value by considering the reductions in material use and labour, reductions in programme, reduced preliminaries and/or early handover and the value of increased floor areas.

The composite steel framed office building in the City of London described in Table 2, Figure 5 and Figure 6 was selected. The selection was based on a building that is tall enough so the benefits are relevant for high rise buildings and short enough, so the results are also relevant to mixed-use low and medium rise structures, either residential or office.

The scheme consists of 21 storeys with an approximate total gross floor area of 80,000m^2. The building structure consists of a slip-formed reinforced concrete primary core, with steel columns supporting composite steel beams and steel-concrete composite floors. Separate from the primary core there exist three secondary cores formed with steel bracing. The overall construction programme for the superstructure was 39 weeks. This included 15 weeks to construct the core, using a slip-form. The erection of the steel frame was the critical path item, as shown in Figure 7.

Design benefits which make use of Toproc Rapid's high 28 day strength can be realised through either reduced element sizes or reduced reinforcement, the approach was to redesign the elements with the aim of providing equivalent structural performance to the elements as designed in the building.

The actual construction sequence used by the Contractor on the project has been interrogated, and reductions in programme attributable to the use of Topflow and Toproc Rapid have been identified. Where the changes to design have reduced the material required (i.e. smaller sections and reduced reinforcement), this will also take less time to pour or place.

Toproc Rapid's high early strength gain has the potential to realise additional programme savings due to the early striking of formwork. These benefits should reduce the structural frame sub-contractors programme with higher level benefits to the main contractor and building owner flowing from lower sub-contractor costs.

There is also the potential for overall programme reduction for the main contractor if the elemental programme savings to the subcontractor programme can benefit follow on trades and the overall project critical path. The benefits of reduced overall programme are calculated considering a reduction in the main contractor's preliminaries, and the value of earlier completion and handover of building to the client.

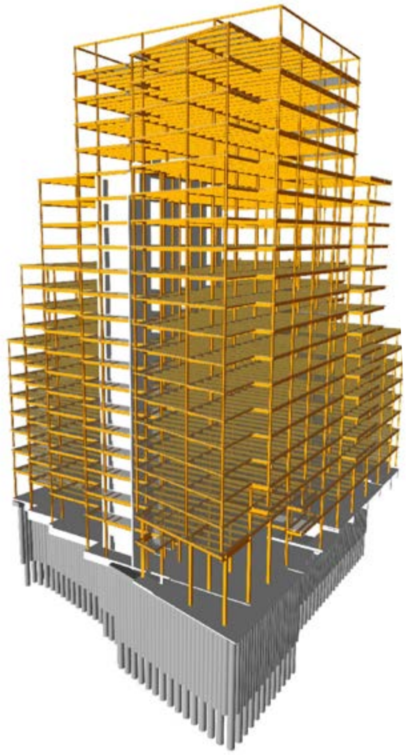


FIGURE 5

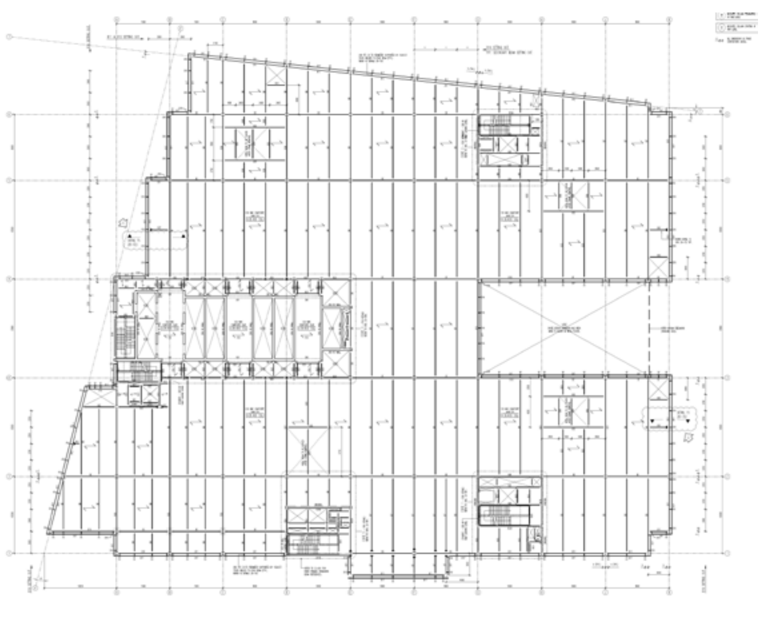
Steel Office Case Study Building
3D View of Structural Frame

Similarly to the element study, costs were calculated for a base case scenario (using conventional concrete mixes) and construction scenario utilising special concretes, including any material, labour or programme savings that can be realised. Value added in terms of increased lettable space and early completion were also considered.

TABLE 2 Steel Framed Case Study Building Key Data

PROJECT TYPE	CITY OF LONDON OFFICE BUILDING
Use	Office
Date of Construction	Completed 2009
Procurement Route	Construction Management
Height	21 storeys
Floor Area	80,000m^2 approx.
Superstructure Frame	Steel frame Composite concrete slabs on metal-decking
Stability System	Slip formed RC core Steel eccentric bracing
Typical Grid	9m x 13.5m

FIGURE 6 Steel Office Case Study BuildingTypical Floor Plan



DISCUSSION OF RESULTS: ELEMENT STUDY

From the summary of cost savings shown in Table 3, it is evident that there are generally savings to be realised when using Toproc Rapid for the structural elements considered and that Topflow SCC provides savings when used in composite slabs, due to its inherent speed of placing.

SHEAR CORES

Toproc Rapid in Shear Cores

This study has found potential design benefits and cost savings from using Toproc Rapid at an elemental level. Formwork is a significant proportion of the cost of jump forming a shear core. Cost reductions of at least 10% are possible from programme-only savings due to the reduction in formwork costs. Making use of Toproc Rapid's high early strength, formwork can be struck after 18 hours instead of 4 days, allowing it to be reused more efficiently. The formwork can then be cleaned and reused elsewhere, reducing the amount of formwork that needs to be hired. This faster formwork rotation cycle can also speed up the programme, the benefits of which are highlighted in the building study.

In addition to the formwork savings, material savings are possible by thinning the wall or reducing reinforcement. A greater reduction is possible for a 300mm wall than a 250mm thick one, due to buckling effects limiting the potential reduction in thickness. However, in taller buildings the axial forces are high, hence there is more scope for material saving. The additional area gained around the thinner walls can bring increased revenues due to the additional lettable area.

Table 4 shows the cost savings when using Toproc Rapid for 250mm and 300mm base wall thickness and Figure 8 shows how the cost varies when using Toproc Rapid compared to the base case when taking into consideration programme only savings, reduced reinforcement and programme savings and reduced size and programme savings for the 300mm thick wall base case.

Topflow in Shear Cores

While Topflow generates savings in labour costs avoiding both the need to vibrate and make good, they are not significant enough to offset the increased cost of concrete at an elemental level. Further savings can be realised by the contractor in relation to placing and compaction plant, which are no longer required.

Topflow is often used for the exceptionally high quality architectural finish it provides. Topflow can also be mixed to be used at higher strengths: in the order of 60 to 80MPa. At such strengths the programme, material and labour benefits described for Toproc Rapid would apply.

FIGURE 7 Extract summary of steel building programme

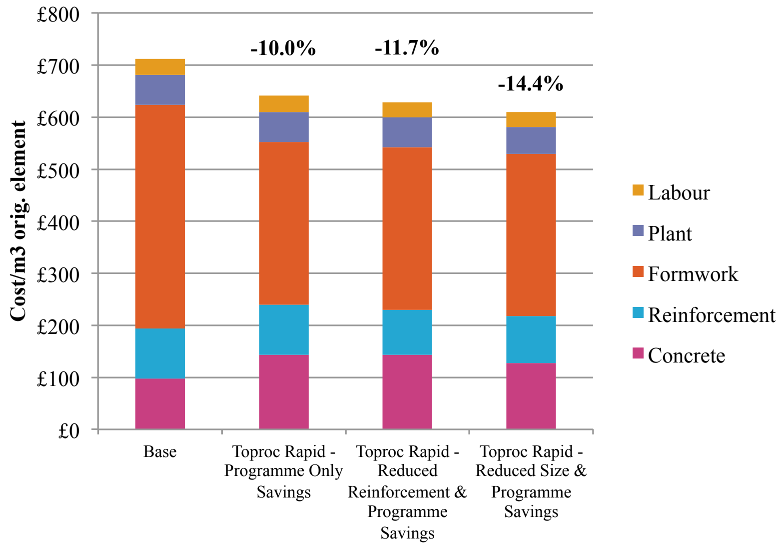
CORE		CONSTRUCTION TIME	START	FINISH
Slipform Core		14w 4d	14/09/2007	21/12/2007
Pre-assemble slipform		2 weeks	14/09/2007	28/09/2007
Assemble slipform		2 weeks	01/10/2007	12/10/2007
Slipform operations		10w 4d	15/10/2007	21/12/2007
Steel frame up to level 4		4w 2d	23/10/2007	21/11/2007
Level 4 to Level 6 Zone 01	Frame	4 weeks	22/11/2007	19/12/2007
	Decking	2 weeks	20/12/2007	16/01/2008
	Concrete to slabs (Level 5)	3 days	30/01/2008	01/02/2008
	Concrete to slabs (Level 6)	1 week	11/02/2008	15/02/2008
Level 6 to Level 8 Zone 1	Frame	2w 3d	16/01/2008	01/02/2008
	Decking	1w 3d	30/01/2008	08/02/2008
	Concrete to slabs (Level 7)	1 week	19/02/2008	25/02/2008
	Concrete to slabs (Level 8)	1 week	04/03/2008	10/03/2008

TABLE 3 Summary of change in costs found for the element study

	TOPROC RAPID		TOPFLOW
	PROGRAMME ONLY	PROGRAMME & DESIGN (BEST CASE)	PROGRAMME ONLY
Shear Cores [1]	-10.0%	-14.4%	+3.7%
Composite Slabs	N/A	N/A	-5.1%

1 For columns and shear cores the value generated through the increase in lettable area can be significant and is in addition to the values presented in this table.

FIGURE 8 Breakdown of cost savings from using Toproc Rapid in shear cores with 300mm initial thickness



RC COMPOSITE SLABS

As Topflow is assumed to have the same structural design properties as a standard concrete mix there are no material reductions to be achieved. However, labour savings are achieved, as Topflow can be poured more quickly and require less finishing than a standard mix. These benefits were highlighted in the building study and the cost savings for this building are shown in Table 5.

DISCUSSION OF RESULTS: BUILDING STUDY

The element study identified potential reductions in programme for shear cores. However, in the building case study, neither the in-situ concrete core nor the composite slabs were on the critical path of the overall programme and the core was slip formed, so the elemental savings have not resulted in a reduced programme. The critical path for this building was driven by the rate of erecting the steel frame.

The use of Toproc Rapid and Topflow could reduce the overall programme, when either the concrete core and/or the composite floors are on the critical path.

Programme reduction could be achieved if the cores are jump-formed (see Table 6). The core construction programme could have been reduced by 40% with a subsequent reduction in the overall programme. This potentially offers huge benefits to the client who commissioned the building: ranging from early release of funds leading to reductions in interest payments, or early letting leading to improved cash flow.

Shear cores were analysed and designed to maintain an equivalent stiffness and limit local buckling of individual wall panels. This resulted in the thicknesses of the long shear wall elements being reduced by 50mm and the shorter shear wall elements being reduced by 60mm.

This in turn resulted in a 20% material reduction. It also allowed the overall area of the shear core to be reduced giving an additional 7m^2 per core per floor. Over the whole building this resulted in an additional usable floor area of 128m^2. The 20% weight saving would have further benefits in reduced substructure loads, not quantified in this study.

Combining the material, plant and labour savings gives a total saving of £267,780 from an estimated core/composite slab package cost of £13,740,568 for the base case building. This represents a saving of 2% on the composite frame construction cost. The estimated total construction cost of the building is £161m.

The additional value of the increased lettable floor areas achieved by reduction in vertical elements area is £69,400 p.a, based on a current market rate of £540/m^2/year as of September 2014.

TABLE 4 Cost savings from using Toproc Rapid in jump-form cores - Office floor height

COMPARISON CASE		COST (£/M^3 ORIGINAL ELEMENT)	COST CHANGE	OTHER SAVINGS [1]
300mm initial thickness	Base Case	£712	-	-
	Toproc Rapid Programme Savings Only	£641	-10%	-
	Toproc Rapid Reduced Reinforcement & Programme Savings	£629	-11.7%	-
	Toproc Rapid – Thinner Wall & Programme Savings	£610	-14.4%	£15/yr
250mm initial thickness	Base Case	£809	-	-
	Toproc Rapid Programme Savings Only	£715	-11.7%	-
	Toproc Rapid Reduced Reinforcement & Programme Savings	£702	-13.1%	-
	Toproc Rapid – Thinner Wall & Programme Savings	£702	-13.2%	£6/yr

1 Additional rental income to the client due to increased lettable floor area, based on £600/m^2 per year rental return

TABLE 5 Cost savings in composite slab and shear core construction

ELEMENT	COST OF BASE CASE	COST INCORPORATING SPECIAL MIXES	CHANGE
Core	£1,772,867	£1,602,234	-9.6%
Composite Slabs	£11,967,701	£11,870,557	-0.8%
Total	**£13,740,568**	**£13,472,791**	**-1.9%**

TABLE 6 Total programme reduction possible in core construction assuming a jump-formed core

CONCRETE	PROGRAMME (EXCL. FORMWORK SETUP, ETC.)	PROGRAMME SHORTENED (DAYS)
Conventional	85	-
Toproc Rapid	51	34

Steel Office Case Study Building

CONCLUSIONS

The purpose of the study was to identify opportunities for design and construction savings in steel frames using special concretes, Topflow (self-compacting concrete) and Toproc Rapid (high early strength concrete), and the overall benefits transferred to the stakeholders of the building.

The study was carried out in two stages; an elemental level and the overall build of the structural frame, using a real commercial office building project in London to quantify the findings.

Table 3 summarises cost savings at an elemental level (negative figures representing savings). Cost benefits are shown for programme only and also for combined programme and design savings when using Toproc Rapid: the former considering cost benefits associated with early strength gain of the element and quick rotation of formwork, and the later, considering programme savings in combination with the best case between a reduction of the element size or bar reinforcement.

In the case of Topflow, because the mechanical properties were considered as per the base case (i.e. a conventional C30/37 concrete), the benefits shown on Table 3 are mainly derived from speed of construction for the construction of floors.

The higher 28 day strength of Toproc Rapid considered in this study (75MPa characteristic strength) gives the designer the opportunity to realise thinner walls and/or reduce the amount of reinforcement with the added value of an increased lettable floor area. Furthermore, the high early strengths of Toproc gives the frame contractor the opportunity to generate additional savings by striking formwork earlier.

Topflow can be placed on metal decking using typically a third of the labour and a quarter of the time compared to a conventional mix. This brings significant programme savings for composite slabs and shear cores as shown in Table 5. Faster construction using Topflow, allows earlier access for follow on trades, both above and beneath the slab.

Table 7 summarises the overall cost savings and value added to commercial office building considered in this study. The cost savings are mainly due to reduced material and labour required when using Toproc Rapid high 28 day strength and reduced labour and plant needed if using Topflow. The value added shown on Table 7 was due to additional lettable or saleable area resulting from the reduction of vertical element sizes.

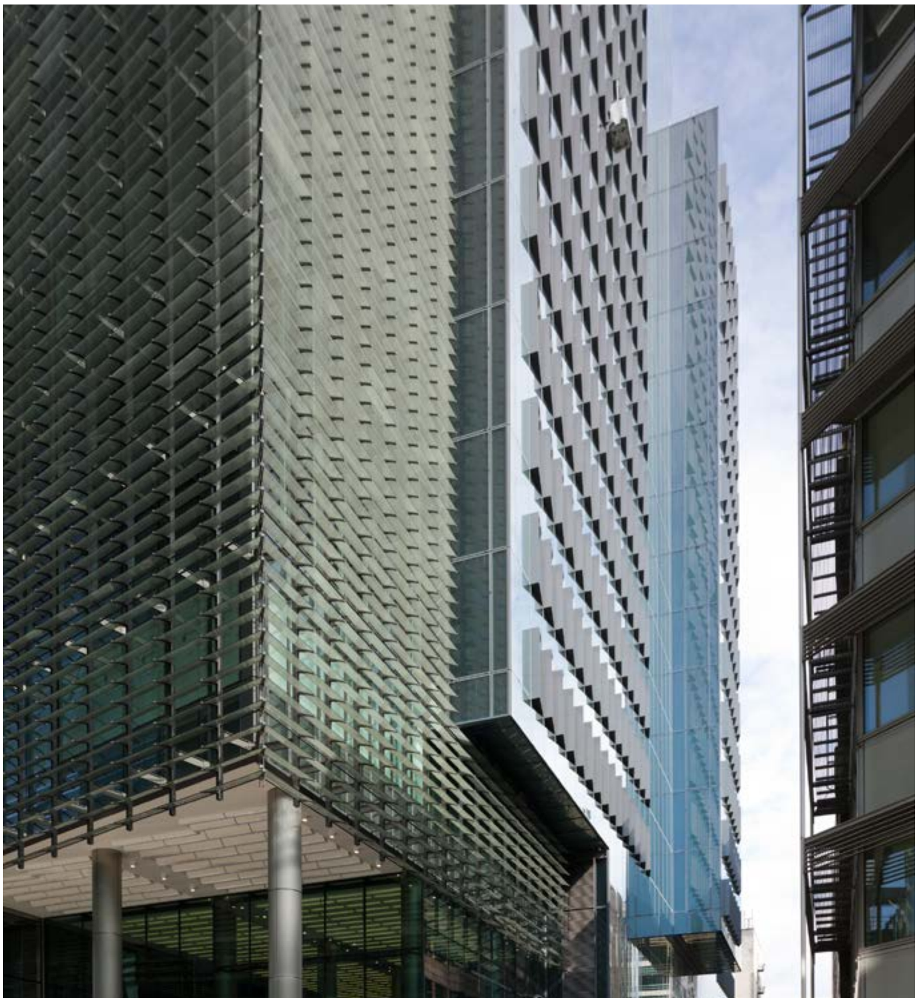
There are other areas in which Toproc Rapid and Topflow concrete mixes can bring value to a project but their commercial benefit are not included within the savings: improvement in health and safety, reduction on site related disruption such as truck movements, noise and working hours.

The building case study was not able to identify significant overall programme benefits because for the chosen base case, the concrete elements were not on the critical path. However, if the concrete core for these buildings had been on the critical path, using Toproc Rapid in jump-form cores, can potentially offer a 40% time saving for the core construction.

The positive results above demonstrate that considering Toproc Rapid and Topflow at the design and construction stage can be beneficial. The greatest benefit is gained if both Toproc Rapid early age and 28 day high strengths are included at the design stage.

TABLE 7 Summary of results from building study

	COST SAVINGS	VALUE ADDED
Concrete-framed residential building	£391,722 including façade cost saving 8.4% reduction in construction cost with respect to cost of structural frame	£175,000 increased sale price due to additional floor area
Composite steel and concrete-framed office building	£267,777 1.9% reduction in construction cost with respect to cost of structural frame	£69,400 increased rental revenue per year due to additional floor area



Steel Office Case Study Building