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ARUP

VALUE OF SPECIAL CONCRETES IN CONCRETE 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 concrete 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 residential building project to quantify the findings.

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, slabs, and walls; and also using a building case study for a typical mid-rise residential reinforced concrete frame building.

The case study building was chosen to be typical of residential construction, a 16 storey residential building construction using flat slabs and concrete cores. The building was 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.

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 13%, 17%, 6% and 10% for columns, shear cores, RC slabs and PT slabs respectively. At the whole-building level, a concrete construction package cost reduction of 7% was found, with improved area metrics adding value equivalent to 8.4% of the concrete construction package.

The main regional focus of the study was the London market, but UK regional variations are also considered. The study considered both in-situ concrete framed buildings and composite steel framed buildings in the residential and commercial office sectors. This report considers the realisable benefits for in-situ concrete framed construction.

INTRODUCTION

Design and construction using conventional concrete for insitu concrete framed multi-storey and high rise building structures has long been an established industry norm 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 (columns, Flat/PT 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 smaller insitu columns, thinner walled shear cores and thinner flat slabs were examined from both design (including early age deflection, punching shear and reinforcement quantities), and commercial (including accelerated build, increasing lettable floor areas) perspectives.

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 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.

Based on data obtained from contractors, 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 was 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.

STUDY METHODOLOGY: ELEMENT STUDY

The element study considers the design of principal structural elements for office and residential loading cases. For each element studied, a typical 'base case element' was selected to establish a standard design 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. Any overall programme savings to the main contractor's construction programme, are not considered in the element study. This was subsequently considered in whole building studies.

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. For cost modelling: material rates were established through market testing with the supply chain and use of internal data. 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 in terms of considering either reducing the element cross section or reducing reinforcement quantities. These were then compared to a base case to evaluate material savings and increasing 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

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. Potential cost savings due to reductions in plant, labour and programme resulting from the use of Topflow were considered.

COLUMNS

Columns 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, a 'base case column' was defined for use as a basis for comparisons. A typical 500mm x 500mm column with 3.1% reinforcement was chosen, as shown on Figure 1.

A series of columns using Toproc Rapid were designed to develop an equivalent or improved capacity compared to the base column and costed to take into considerations aspects such as steel bar fixing, shuttering installation and removal, concrete placing and curing as explained in Table 1.

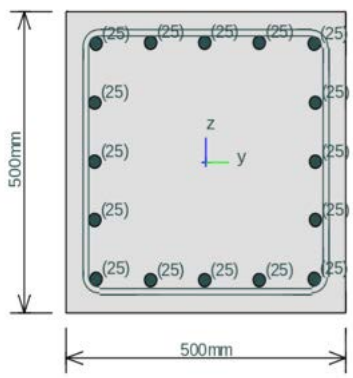


FIGURE 1

Column base case - 500x500 C30/37 16H25

STEP	IMPACT OF USING TOPROC RAPID
Construct "kicker"	None
Position 2 sides of shuttering	None
Position and tie-in pre-fabricated steel bar cage	Reduced fixing time where reinforcement quantity is reduced.
Position final 2 sides of shuttering and carry out pre-pour checks	None
Place/position concrete	Marginal – placing time is governed by manoeuvring of skip between columns as opposed to the volume of concrete.
Concrete curing/initial hardening	none - Normal setting concrete can strike columns same day as cast & re-use formwork for further columns. No further advantage would be achieved from using Toproc Rapid.
Ease off, remove shutters and clear	None

TABLE 1 Impact of Toproc Rapid on Typical Column Construction

SHEAR WALLS

Similarly to columns, a 'base case shear wall' was defined to use for comparisons. A typical U-shaped wall was chosen, as shown in Figure 2. 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 wall thicknesses were investigated, 300mm and 250mm, to show the impact on buckling and any material savings. Cores were then designed using Toproc Rapid high 28 day strength, 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 as per Table 2.

STEP	IMPACT OF USING TOPROC RAPID
Erect scaffold and construct inner face of shuttering	None
Construct box-outs onto the shuttering	None
Position and tie reinforcement cage onto shuttering	Reduced fixing time where reinforcement quantity is reduced.
Position outer face of shuttering	None
Place/position concrete	Reduced placing time where concrete quantity is reduced.
Concrete curing/initial hardening	Reduced time on site due to earlier formwork reuse.
Dismantle shutters for cleaning and relocation to higher level	None

TABLE 2
Impact of Toproc Rapid on Typical Core Wall Construction

RC SLABS

The reinforced concrete slabs were designed using RAPT (Reinforced and Post Tensioned design software). For the purposes of the element study, a typical grid of 8.5m x 8.5m spacing was defined (with smaller end bays) as shown in Figure 3. The base case RC slab was a C30/37 slab 280mm thick with 60 kg/m^3 and 44 kg/m^3 of reinforcement for office and residential loadings respectively.

The higher 28 day strength of Toproc Rapid has advantages in terms of punching shear and also allows thinner slabs to be designed. The design loadings were applied to the slabs, and they were sized and reinforced for the resulting moments. To account for the rapid gain in strength of Toproc Rapid in the first few days after pouring, the 4 day strength (at de-propping) is assumed to be C40/50.

The individual steps associated with constructing a slab and the impacts of using Toproc Rapid at each stage of construction, ie striking, peak construction and service, were considered to estimate cost savings taking into consideration programme only savings, reduced reinforcement and programme savings and reduced size and programme savings. The effects of using Toproc Rapid, are summarised in Table 3 below.

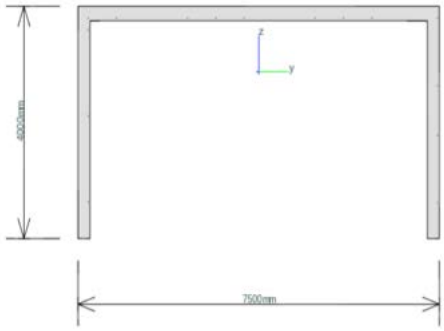


FIGURE 2
Shear core base case - C30/37 250 thick & H16s@300crs

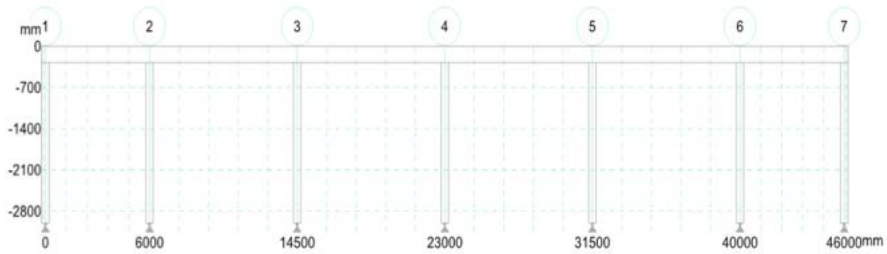


FIGURE 3
Slab base case - 280mm C30/37 Typ grid 8.5m x 8.5m

STEP	IMPACT OF USING TOPROC RAPID
Pour concrete to slab area required	Where less concrete is required, the time and resource needed to pour is reduced.
Carry out initial stress of post tensioned strands	Can stress all at once if strength >22MPa by 24h after casting.
Carry out second stress of post tensioned strands	Stressing can be carried out earlier, reducing the required time (stressing on day 1 as opposed to day 3 to 4)
Strike formwork	Formwork can be struck on day 2 after the stressing has been carried out (traditionally struck on day 5).
Strike props	Props can be struck earlier

TABLE 3 Impact of Toproc Rapid on Typical Slab Construction

It is important to highlight that in this study and when using high early strength concretes, the main cost savings are related to early striking of formwork and back propping as well as those related to a reduction in reinforcement and concrete quantities, due to improved element design achieved when using higher 28 day strength concrete.

When using Topflow, at same strength as a standard C30/37, the main benefits are programme related due to the speed and ease of placing and finishing Topflow, to achieve SR2 finish without vibrating, compacting and floating the slab. In terms of cost modelling for the slab, 50% and 66% plant and labour cost saving respectively were achieved.

PT SLABS

The higher 28 day strength of Toproc Rapid allows thinner post tensioned (PT) slabs to be designed. The PT slabs were designed using RAPT (Reinforced and Post Tensioned design software), using the same grid and loading as the RC slabs. A PT slab was then designed to these criteria and defined the 'base case PT slab.' Bar reinforcement for the PT slabs was designed on the basis of 32 kg/m^3 for both office and residential loading conditions.

Because of the rapid gain in strength in the first days after pouring, the 4-day strength (at de-propping) is assumed to be C40/50).

In PT slabs the tendons are stressed in two stages, the first stage (25% of final prestress) usually applied when the concrete has gained adequate strength for the anchorage being used (typically 7-9 MPa), and the second stage (75% of the final prestress) when the concrete strength reaches 22 MPa for 12.7 dia strands and 25 MPa for 15.2 strands (typically between day 4 and 7).

With Toproc Rapid, the full prestress force could be applied once the concrete has reached 22/25MPa, most likely within the first day of casting the slab (see Tables 3 and 4 for a description of the above benefits in a traditional construction method of PT slabs and the effects in cost modelling).

The individual steps associated with constructing a PT slab in a traditional format and the impacts of using Toproc Rapid at each stage are described in Table 4.

STEP	IMPACT OF USING TOPROC RAPID
Pour concrete to slab area required	Where less concrete is required, the time and resource needed to pour is reduced.
Carry out initial stress of post tensioned strands	Can stress all at once if strength >22MPa by 24h after casting.
Carry out second stress of post tensioned strands	Stressing can be carried out earlier, reducing the required time (stressing on day 1 as opposed to day 3 to 4)
Strike formwork	Formwork can be struck on day 2 after the stressing has been carried out (traditionally struck on day 5).
Strike props	Props can be struck earlier

TABLE 4 Impact of Toproc Rapid on Typical PT Slab Construction

STUDY METHODOLOGY: BUILDING STUDY

Real buildings were chosen to base the case study on, and 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. 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 reduced façade areas due to thinner slabs and increased floor area due to smaller elements 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 concrete-framed residential building described in Figure 4 and Table 5 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.

FIGURE 4
Concrete residential building elevation

The scheme consists of three blocks, 9, 16 and 7 storey buildings, rising from a two storey podium, which is excluded from this study. The blocks are of similar construction, each with a reinforced concrete slip-form central core. The building is L shaped, with a 16m short dimension. The columns are arranged on

an 8m x 8m grid and the floor slabs are 225mm deep PT concrete and the roof slabs are 300mm deep RC slabs.

Figure 5 shows the construction programme for the 9 storey block. It can be seen that the core was slip formed in 8 weeks and the cycle time per floor is 10 days with tendons typically stressed in two stages.

Design benefits which make use of Toproc Rapid's high 28 day strength can be realised through either reduced element sizes or reduced reinforcement and 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 less 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, falsework and back propping and due to the removal of one stage of post-tensioning. These benefits should reduce the structural frame sub-contractor's programme, with higher level benefits to the main contractor, and building owner flowing from lower sub-contractor costs.

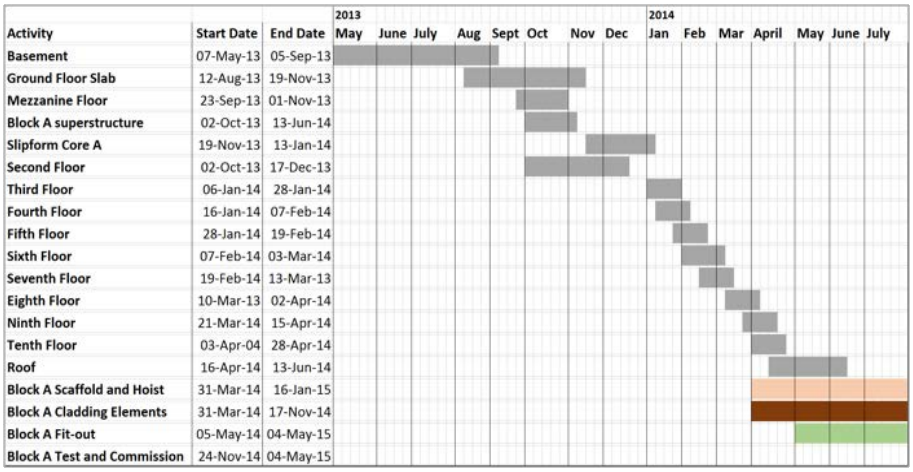
There is also the potential for overall programme reduction for the main contractor if the elemental programme savings to the subcontractor programme can benefit follow on trades and the overall project critical path. The benefits of reduced overall programme are calculated considering a reduction in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

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 5 Concrete case study building key facts

PROJECT TYPE	COMMERCIAL RESIDENTIAL DEVELOPMENT WITH GROUND FLOOR COMMERCIAL
Location	Central London (Zone 1)
Date of Construction	Q2 2013 to Q2 2015
Procurement Route	Construction Management by Developer
Height	Varies from 7 to 16 storeys
Floor Area	16,500m^2 approx.
Frame	Reinforced Concrete PT flat slab with blade columns
Stability System	Slip-formed Reinforced Concrete Cores
Typical Grid	8m x 8m
Sustainability	Code for Sustainable Homes Level 4

FIGURE 5 Concrete Frame Programme for 9-storey residential



Activity	Start Date	End Date
Basement	07-May-13	05-Sep-13
Ground Floor Slab	12-Aug-13	19-Nov-13
Mezzanine Floor	23-Sep-13	01-Nov-13
Block A superstructure	02-Oct-13	13-Jun-14
Slipform Core A	19-Nov-13	13-Jan-14
Second Floor	02-Oct-13	17-Dec-13
Third Floor	06-Jan-14	28-Jan-14
Fourth Floor	16-Jan-14	07-Feb-14
Fifth Floor	28-Jan-14	19-Feb-14
Sixth Floor	07-Feb-14	03-Mar-14
Seventh Floor	19-Feb-14	13-Mar-13
Eighth Floor	10-Mar-13	02-Apr-14
Ninth Floor	21-Mar-14	15-Apr-14
Tenth Floor	03-Apr-04	28-Apr-14
Roof	16-Apr-14	13-Jun-14
Block A Scaffold and Hoist	31-Mar-14	16-Jan-15
Block A Cladding Elements	31-Mar-14	17-Nov-14
Block A Fit-out	05-May-14	04-May-15
Block A Test and Commission	24-Nov-14	04-May-15

DISCUSSION OF RESULTS: ELEMENT STUDY

From the summary of cost savings shown in Table 6, it is evident that there are savings to be realised when using Toproc Rapid for all of the structural elements considered and that Topflow SCC provides straight savings when used in RC slabs, due to its inherent speed of placing.

This report is focused on these savings and a summary of the results for each element type follows.

COLUMNS

Toproc Rapid Benefits

Figure 6 shows how the costs vary when using Toproc Rapid compared to the base case, taking into consideration programme only savings, reduced reinforcement and programme savings and reduced size and programme savings.

TABLE 6 Summary of cost savings using Toproc Rapid

	TOPROC RAPID		TOPFLOW
	PROGRAMME ONLY	PROGRAMME & DESIGN [2] (BEST CASE)	PROGRAMME ONLY
Columns [1]	+4.8%	-12.8%	+1.8%
Shear Cores [1]	-10.0%	-16.7%	+3.7%
RC Slabs	-0.7%	-5.7%	-6.1%
PT Slabs	-5.1%	-9.9%	N/A

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.

2 Where more than one case was analysed (e.g. office and residential) the most beneficial results are reported. See individual sections for detailed results.

This study has found potential design benefits and cost savings from using Toproc Rapid at an elemental level. Columns show significant cost savings due to reduced size and/or reinforcement quantity. Reducing column sizes brings additional benefits such as improved aesthetics and increased lettable space area (approx £23 per column a year additional revenue).

Topflow Benefits
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. However, further savings can be realised by the contractor in relation to placing and compaction plant, which are no longer required. Also Topflow is often used for the exceptionally high quality architectural finish it provides as well as its potential to be used at higher strengths: in the order of 60 to 80MPa.

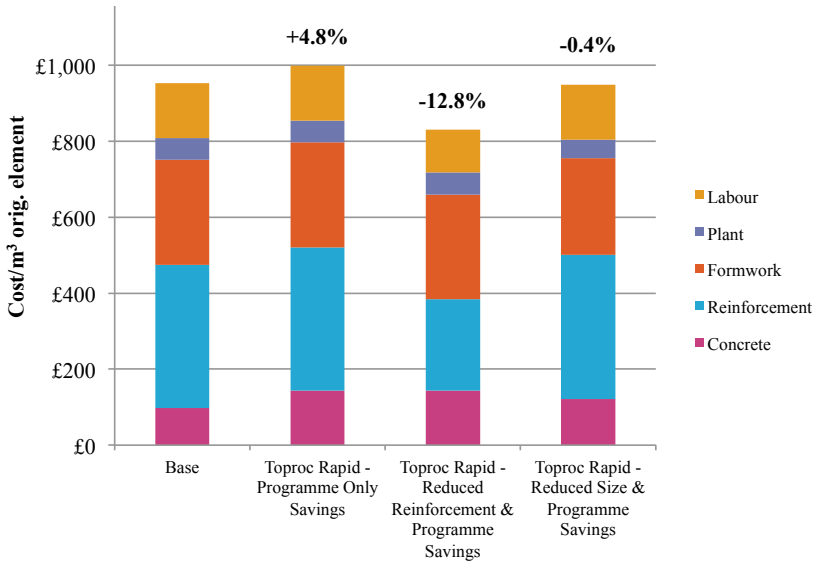


FIGURE 6 Breakdown of cost savings from using Toproc Rapid in columns

SHEAR WALLS

Toproc Rapid Benefits
Figure 7 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.

Formwork is a significant proportion of the cost of jump forming a shear core. Significant cost reduction (at least 10%) is 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 far 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 will also speed up the programme.

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. Similar to columns, the additional area gained around the thinner walls can bring increased revenues due to the additional lettable area.

Topflow Benefits
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 as shown in Figure 8. However, further savings can be realised by the contractor in relation to placing and compaction plant, which are no longer required. Also Topflow is often used for the exceptionally high quality architectural finish it provides as well as its potential to be used at higher strengths: in the order of 60 to 80MPa.

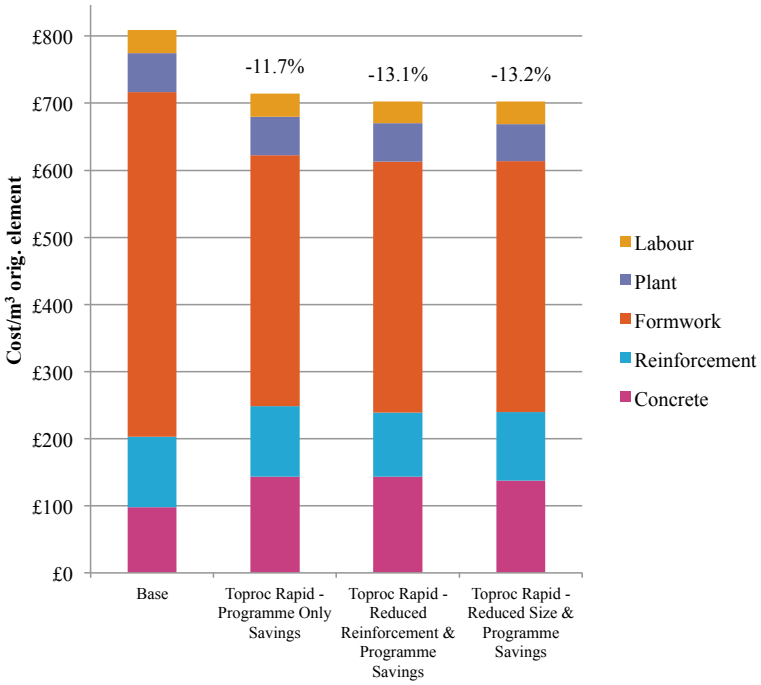


FIGURE 7 Breakdown of cost savings from using Toproc Rapid in shear cores

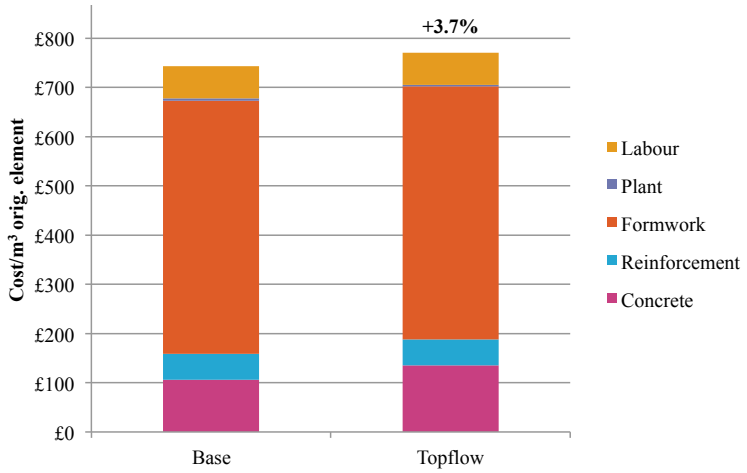


FIGURE 8 Breakdown of cost savings from using Topflow in shear cores

RC SLABS

Toproc Rapid Benefits

The overall cost saving and their breakdown for a RC slab comparing the base case and programme benefits provided by Topflow are shown in Figure 9 and Table 7.

The use of Toproc Rapid in RC slabs provides significant reduction in formwork costs due to its faster rotation, while a reduction in the subcontractor's preliminaries due to the increased speed of the work provides additional benefit. Additionally, material savings are also possible when taking into consideration the high 28 day strength of Toproc Rapid, by thinning the slab or reducing reinforcement. However, for very thin slabs the governing condition is often fire or vibration performance rather than pure strength, so this saving cannot be relied upon in all cases.

Topflow benefits

Design benefits are not expected from Topflow since, for the study, the slabs were designed using the same mechanical properties as conventional base case concrete. However, there are cost reductions for RC slabs derived from the increased speed of construction provided by Topflow as seen in Figure 10, leading to reductions in labour and plant. Further savings can be achieved where there is a requirement for SR2 finish leading to the removal of epoxy leveling/finishing materials or where low noise levels provided by Topflow give the contractor more flexibility when either the local authority or client impose time / noise restrictions on site activities.

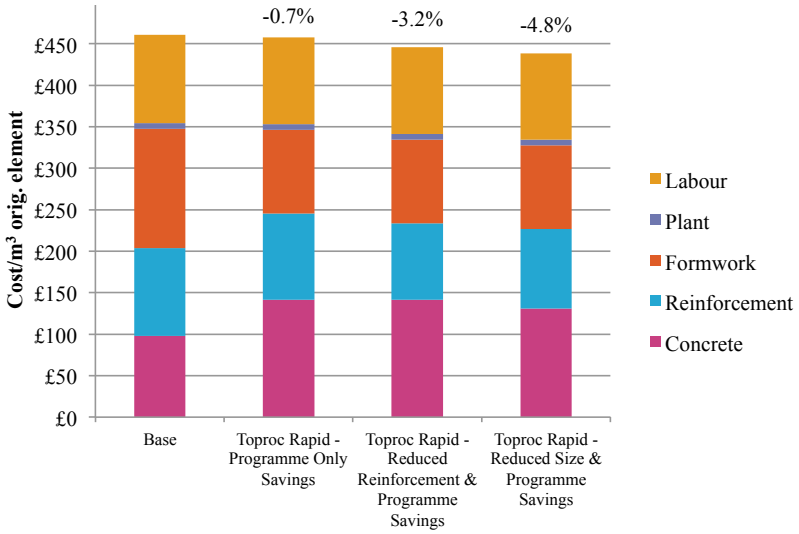


FIGURE 9 Breakdown of cost savings from using Toproc Rapid in RC slabs with residential loading

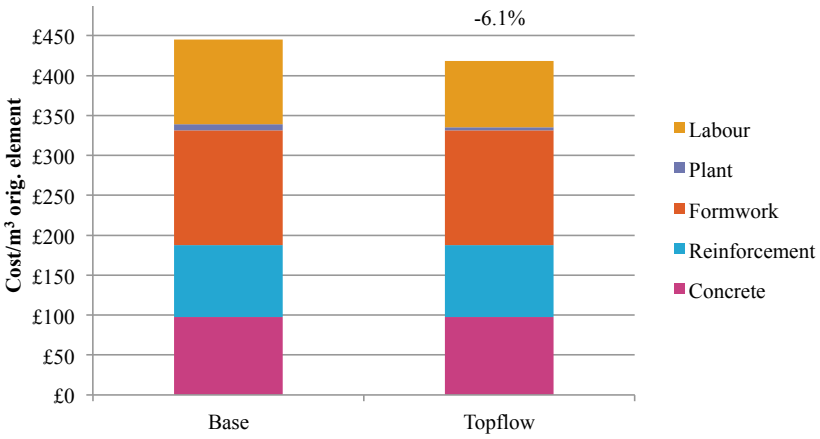


FIGURE 10 Breakdown of cost savings from using Topflow in RC slabs

TABLE 7 Summary of RC slab study

LOADING	CASE	CONCRETE	T (MM)	CONCRETE REDUCTION	REBAR RATE [1] (KG/M³)	REBAR CHANGE	PUNCHING SHEAR STUDS (NO.)	PUNCHING SHEAR REDUCTION
Office	Base case	C30/37	280	-	60	-	148	-
	Reduced reinforcement	Toproc Rapid C60/75	280	-	60	0%	104	-30%
	Reduced slab thickness	Toproc Rapid C60/75	260	-7%	64	0%	120	-19%
Residential	Base case	C30/37	280	-	44	-	104	-
	Reduced reinforcement	Toproc Rapid C60/75	280	-	44	0%	64	-38%
	Reduced slab thickness	Toproc Rapid C60/75	260	-7%	47	0%	64	-38%

[1] Includes +15% for laps

PT SLABS

For PT slabs, similar programme and material savings to RC slabs are achieved with the additional benefit of stressing the tendons in a single operation instead of a two stage process, giving significant labour savings as summarised in Table 8 and Figure 11. This would also offer significant programme improvements.

Toproc Rapid Benefits

The overall cost saving and their breakdown for a RC slab comparing the base case and programme benefits provided by Topflow are shown in Figure 9 and Table 6.

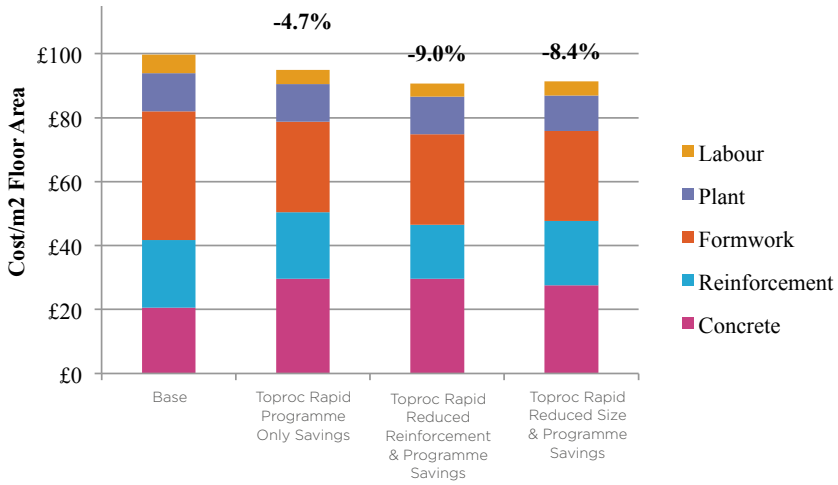


FIGURE 11 Breakdown of cost savings from using Toproc Rapid in PT slabs with office loading

TABLE 8 Summary of PT slab study

LOADING	CASE	CONCRETE	T (MM)	CONCRETE REDUCTION	REBAR RATE [1] (KG/M³)	REBAR CHANGE	PUNCHING SHEAR STUDS (NO.)	PUNCHING SHEAR REDUCTION
Office	Base case	C30/37	210	-	24	-	184	-
	Reduced reinforcement	Toproc Rapid C60/75	210	-	17	-29%	128	-30%
	Reduced slab thickness	Toproc Rapid C60/75	195	-7%	26	0%	172	-7%
Residential	Base case	C30/37	210	-	0	-	108	-
	Reduced reinforcement	Toproc Rapid C60/75	210	-	0	0%	72	-33%
	Reduced slab thickness	Toproc Rapid C60/75	195	-7%	0	0%	88	-19%

[1] Includes +15% for laps

DISCUSSION OF RESULTS: OVERALL BUILDING

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 each of the shear wall elements being reduced by 15mm. This gave a 6% material reduction on the shear cores. It also allowed the overall area of the shear core to be reduced giving an additional 0.2m² per core per floor. Over the whole building this resulted in an additional usable floor area of 13.2m².

For columns, reducing the size of the elements in both directions was explored. Larger savings are achieved by reducing the short side (from 800 x 225 to 800 x 210) with a material reduction of 7% and area saving of 3.52m² per floor.

PT slabs were designed using Toproc Rapid to achieve the same deflection performance as in the original design. This resulted in a 15mm reduction in the thickness of the slabs from 225mm to 210mm. This gave in turn a 7% reduction in slab concrete volume. The thinner slabs reduced the height of the building by 15mm per floor. Similarly for RC slabs, the original slab can be reduced by 25mm from 300mm to 275mm, which represents a reduction of 8% in material. The reduction in the thickness of both PT and RC slabs results in a façade area reduction of 75m² across the three blocks.

Table 9 and Table 10 (next page) summarise the above design benefits when using special concretes and the associated cost savings. The cost savings associated with the reduction in façade area is £70,518, which also includes an estimate of preliminaries reduction.

The programme for the concrete frame was not on the critical path for this development and the core was slip formed, therefore the savings that could potentially be realised by using Toproc Rapid high early strength concrete would not impact on the overall programme for this project.

Combining the material, plant and labour savings and the reduced façade area

TABLE 9 Summary of design changes realised in the concrete-framed case study

ELEMENT	DESIGN CHANGE	MATERIAL CONSEQUENCE
Shear cores	Wall thickness reduced from 250mm to 235mm	Structural material reduced by 6%: concrete volume reduced by 40m³, reinforcement tonnage reduced by 8 tonnes.
Columns	Typical 800mmx225mm column reduced to 800mmx210mm column	Structural material reduced by 7%: concrete volume reduced by 11m³, reinforcement tonnage reduced by 4 tonnes
PT slabs	Slab thickness reduced from 225mm to 210mm	Concrete volume reduced by 7% / 270m³: Punching shear unchanged
RC slabs	Slab thickness reduced from 300mm to 275mm	Concrete volume reduced by 8% / 44m³: Punching shear unchanged.

gives a total saving of £391,722. This is compared to an estimated concrete package cost of £4,650,893 for the base case building. This is a saving of 8.4% with respect to the concrete frame construction cost. The estimated total construction cost of the building is £19M. Also, based on current market rates, the added value of the increased floor areas achieved by reduction in vertical elements area is £175,000.

The building study identified cost savings and additional value added mainly in the form of additional floor area when utilising special concrete mixes such as Toproc Rapid (high early strength concrete) and Topflow (self-compacting concrete). Table 12 summarises the cost savings which are mainly due to reduced material use due to taking advantage of Toproc Rapid's high 28 day strength and subsequent reduction in required façade area and, a reduction in the required amount of labour, due to less materials being quicker to place with Toproc Rapid and the reduced labour and plant needs of Topflow.

There are other areas in which utilising Toproc Rapid and Topflow instead of conventional concrete mixes can bring value to a project. Primarily these are associated with health and safety due to a reduction in labour and site congestion, and improving site environmental conditions due to reduction in truck movements and plant utilisation, as well as the potential of laying Topflow out of hours because of the low noise levels associated with its installation.

The element study identified reductions in programme for shear cores, RC slabs, PT slabs and composite slabs. However, in the building study, the elemental savings have not resulted in a reduced programme because the concrete frame was not in the critical path of the overall programme and the core was slip formed, therefore the savings that could potentially be realised by using Toproc Rapid would not impact on the overall programme in this instance.

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

TABLE 10 Cost savings in concrete-framed case study

ELEMENT	COST OF BASE CASE	COST INCORPORATING SPECIAL MIXES	CHANGE
Cores	£737,848	£697,372	-5.5%
Columns	£222,774	£215,510	-3.3%
PT slabs	£3,372,214	£3,112,974	-7.7%
RC Slabs	£318,057	£303,832	-4.5%
Total	£4,650,893	£4,329,689	-6.9%

TABLE 11 Total programme reduction possible in concrete building case study (block B, 16 storeys) assuming a jump-formed core.

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

Concrete Frame

The concrete frame programme is determined by the floor-by-floor cycle time. The high early-strength gain of Toproc Rapid can provide programme benefits at the interface between the concrete sub-contractor and follow-on trades, by reducing the length of time back-props are needed for each floor: allowing follow-on trades to access the structure earlier. To realise this saving, the procurement process needs to recognise the opportunity and coordinate the follow-on trades (typically the façade sub-contractor) to work in step and immediately behind the concrete works.

In the case of a concrete framed building with higher imposed floor loads in the order of 5 kPa and above, additional benefits can be captured because the construction loads are smaller than the design floor loads. Therefore, there is no need to share the construction loads between floors, provided that the floor below that being constructed has reached its design strength. Toproc Rapid's high early strength makes this possible, so fewer levels of back-props are needed, allowing follow-on trades earlier access to floor plates. This benefit is also independent of building size.

Programme reduction could be achieved if the cores are jump-formed. The possible total programme benefit which could have been realised had the concrete frame building been jump-formed rather than slip-formed are shown in Table 11.

The core construction programme could have been reduced in 40% and the total programme could have been reduced by 5%. 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.

Finally, the buildings selected were medium height (10-25 floors) to allow the benefits relevant to towers to be highlighted, but also ensure that tower effects do not govern and hence the results will also be relevant to mixed-use low and medium rise structures. Taller developments are planned around London and beyond, which can take advantage of the higher design strength of Toproc Rapid to reduce element sizes and thereby generate additional area within the building.

While the relative ratio of labour to material costs may vary regionally, it is considered that the cost savings should be broadly applicable across the UK. However, the additional value calculations will be sensitive to location as they are based on market rental yields. Outside London, whilst there will be less high-rise construction: using medium rise buildings in this study makes it more widely applicable.

CONCLUSIONS

The purpose of the study was to identify opportunities for design and construction savings in concrete 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 residential building project to quantify the findings.

Table 12 summarises the cost savings at an elemental level (negative figures represent savings). Costs benefits are shown for programme only and programme and design savings when using Toproc Rapid, the former considering costs 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 (ie a conventional C30/37 concrete), the benefits shown in Table 8 (p8) are mainly about 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 columns and/or reduce the amount of reinforcement, with the added value of an increased lettable floor area. Furthermore, the high early strengths of Toproc Rapid gives the frame contractor the opportunity realise further savings by striking formwork loading the structural elements earlier. In the case of RC Slabs and PT slabs, the main cost savings are provided by the reduction in thickness of the slabs when the high early strength of Toproc Rapid is considered in the design, with some programme cost reduction associated with the early strike and removal of formwork and back-propping. In the case of PT slabs, programme and design savings are observed owing to the early and single stage prestress of the tendons.

Topflow can be placed using typically a third of the labour and a quarter of the time compared to a conventional mix. This brings significant programme savings for RC slabs as shown in Table 12.

Table 13 summarises the overall cost savings and value added to the residential 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 subsequent reduction in required facade area and, reduced labour and plant needed if using Topflow. The value added shown on Table 13 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 studies were not able to identify significant overall programme benefits because for the chosen case study, the concrete elements were not on the critical path. However, if the concrete frames for these buildings would have been on the critical path, up to two weeks could have been saved through using Toproc Rapid. Using Toproc Rapid in jump-form cores, can potentially offer a 40% time saving for the core construction. For the purposes of illustration it is estimated that this could translate into a 5% reduction in total programme.

These positive results show that the appropriate consideration of Toproc Rapid and Topflow at the design and construction stage can be beneficial, and that most benefit is gained if the designer includes the benefit of both early strength and high 28 day strength.

TABLE 12 Summary of change in costs found for the element study

	TOPROC RAPID		TOPFLOW
	PROGRAMME ONLY	PROGRAMME & DESIGN [2] (BEST CASE)	PROGRAMME ONLY
Columns [1]	+4.8%	-12.8%	+1.8%
Shear Cores [1]	-10.0%	-16.7%	+3.7%
RC Slabs	-0.7%	-5.7%	-6.1%
PT Slabs	-5.1%	-9.9%	N/A
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.

2 Where more than one case was analysed (e.g. office and residential) the most beneficial results are reported. See individual sections for detailed results.

TABLE 13 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