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Effect of steel fibres on the performance of an economical ultra-high strength concrete

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Abstract

This study examines the use of steel fibres in enhancing the ductility of an economical ultra-high strength concrete (UHSC). The adding of fibrous material with very small geometry in this mixture is an effective solution to improve its ductility and prevent its brittle failure which is a common characteristic of UHSC. Different mechanical properties of reinforced and unreinforced concrete (e.g., slump flow, compressive, splitting tensile strength tests and failure modes) were taken into account to find out the efficiency of micro steel fibres. The test results showed that concrete containing 25 mm length and 0.20 mm diameter steel fibres at a volume fraction of 0.5% not only presented a reasonable improvement in ductility performance but also ensured cost-effectiveness. The cost evaluation conducted on several existing mix designs is also introduced in this study to investigate the influence of various steel fibre contents on the total cost of concrete so that figure out the lowest budget solution. The evaluation shows the high price of fibre reinforcement in which an addition of steel fibres by 5% volume could increase 7% of the total concrete cost.

Keywords: Ultra-high strength concrete; fibre-reinforced concrete; micro steel fibres;

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ductility index; post-peak behaviour; cost evaluation

1 INTRODUCTION

UHSC have been well-documented as one of the latest topics of remarkable engineering importance. Unlike a normal strength concrete mix, UHSC were generally applied different binder content, types of aggregate, low dosage of water and several types of substituent cementitious materials. The binder content in UHSC was usually higher than that of normal concrete to minimize the capillary porosity in the inner concrete structure.[1] In terms of aggregate usage, there was a wide range of inert granular materials adopted by many researchers. Aggregates in UHSC could be common rock types such as basalt,[2,3] granite,[4] and bauxite[5] or only fine aggregate such as sand[6] and specially graded aggregates (silica quartz and quartz powder[7,8]). Several proposed mix designs incorporated coarse aggregate with a maximum size up to 20 mm.[9] However, in a vast body of literature, coarse aggregates were suggested not exceeding 10 mm in size to ensure the proper quality of UHSC.[10-12] On the other hand, in the concrete mix with compressive strength below 50 MPa, substituent cementitious materials such as ground granulated blast furnace slag, silica fume or fly ash were mostly absent. The presence of these very fine materials in a UHSC mix could significantly improve its overall performance as they were capable of filling in the void between aggregates and cement paste so that increasing concrete density.

One of the most important factors playing a key role in the performance of concrete was water content. In many existing studies, the water-to-binder (*w/b*) ratio, which varied from 12.5%,[11] 15%,[13] 20%,[14] and up to 30%,[15] could produce UHSC with compressive strength around 150 MPa. Using a very low dosage of water, the fresh mixture would be so consistent that make concrete unworkable. This was how water-reducing agents or superplasticizers emerged as the solution. This admixture helped wet concrete to meet a demanded flowability and gave an advantage to numerous construction processes such as pumping concrete to high points, casting, poring and compacting concrete.[16] Nevertheless, the price of superplasticizer was so expensive compared to other ingredients that could occupy up to 50% of total material cost in several existing UHSC mix designs.[17] Hence, the correlation between the water and superplasticizer content should be considered carefully for concrete to achieve an appropriate flowability, a good strength as well as a reasonable manufacturing cost.

Special curing approaches could make a huge impact on the mechanical properties of concrete. It is well-documented that several severe treatments easily increased concrete strength exceeding 200 MPa. For instance, hot dry air, water or steam were investigated by Shin et al.,[11] Park et al.,[18] and Magureanu et al.[19] while high pressure was reported by Ehab et al.[20] and Ipek et al.[21] The major drawback of these curing conditions was their complexity and difficulty causing a high cost of manufacturing and poor practicality.[18] As a result, these mix designs were mostly experimented in laboratory or fabricated in small-scale structural components.

Concrete has been a brittle and fragile material so that easily cracked under tensile loading. To overcome this nature of plain concrete, fibre reinforcement came as one of the most effective solutions[19-23] which effectively enhanced their structural performance in concrete post-cracking behaviour.[24] The improvement was a consequence of high tensile carrying capacity in which fibres worked as an energy-absorbing material in the concrete matrix and governed the crack development.[25] At the points of cracking, fibrous materials formed numerous bonding bridges to subject to tensile stresses, minimized the crack propagation and prohibited abruptly failure of concrete structures. In terms of material catalogue, fibres could be made of various materials such as steel, synthetic,[26] graphite, carbon aramid,[27] polymer[28-30] or glass.[31] Among them, steel fibres have been in the most popular and common usage due to their superior advantage.[32] Unlike other materials, concrete involving steel fibres were proved to perform excellently under both tension and compression.[33] For example, He et al.[34] reported that steel fibre-reinforced concrete performed better in compressive strength test than concretes added polypropylene or polyvinyl alcohol fibres. In terms of fibre dimension, various sizes of steel fibre have been carried out by numerous experimental studies. According to the database of Larsen and Thorstensen[35] collecting works involving micro steel fibres, a majority of investigations used straight fibres having a length (*L*) and diameter (*D*) greater than 13 mm and 0.2 mm,[36-46] respectively, while hooked-end fibres with length of 30 mm and diameter from 0.3 to 0.6 mm were most repeatedly examined.[40,42,44,47-52] Only a minority of researchers considered smaller fibres such as *L/D* of 11/0.12 by Alomayri et al.,[53] 9/0.15 by Le Hoang and Fehling,[54] 8/0.20 by Arel,[55] Nehdi et al.,[56] and Abbas et al.,[8] 7/0.15 by Haque et al.,[57] 6/0.20 by Wu et al.[58] and Balanji et al.,[59] 6/0.16 by Prem et al.[60] and Gesoglu et al.[61] or 6/0.15 by Erdogdu et al.[62] The benefit of micro steel fibres has been well-documented in the literature.[35] Reducing the size of fibres could obviously provide a greater number of fibres than that of large fibre geometry in the same concrete batch. Applied smaller fibre size, the cementitious matrix was able to gain more thick dispersal of fibre so that effectively govern the expansion of microcracks in concrete.[63] A large number of fibres also increased the homogeneity or uniformity of internal concrete structure, hence partially improving the performance of UHSC. The limited presence of very small fibres in the literature was mainly because they have been in short supply due to the difficulty in production such as manufacturing amorphous micro steel fibre.[64]

In the literature, various contents of fibre in high strength concrete have been explored by many scholars. For example, Chkheiwer & Kadim[51] studied the mechanical behaviour of fibre-reinforced concrete at volume fractions V_f of 0.5%, 1.0%, 1.5%, 2.0% and 2.5% under various heat curing conditions. Abbas et al.[8] and Pourbaba et al.[65] experimented a mixture with fibre volume up to 6.0%. It has been found in these studies that there was an improvement in the compressive strength of UHSC when increasing fibrous material dosage. In the study of Gesoglu et al.,[61] a fibre volume of 0.25% was reported to make inconsequential improvement to the flexural, tensile strength and fracture energy of concrete compared to other specimens using more fibre. However, it was not always the case that increasing the number of fibrous materials certainly provided an effective reinforcement for concrete. UHSC involving a high content of fibre was reported to have poorer performance in many experimental investigations because a great deal of fibre tended to agglomerate into a cluster while more air was entrapped in the concrete matrix during the mixing process.[54,66] Furthermore, in terms of economy, a high content of steel fibre definitely caused buildup to the material cost of UHSC well-stated to be very expensive in advance. Hence, this present study considered fibre volume fractions of 0.5% and 1.5% to maintain cost-effectiveness as well as offer a sufficient ductile improvement to the proposed mix design. The difference in fibre distribution in concrete cylinders incorporating two fibre volume fractions was shown in Figure 2.

Despite many great benefits, UHSC have not been presented widely in constructions as it should be due to several reasons. Firstly, the mechanical performance of UHSC was typically dominated by brittle failure which restricted them from structures subjected to bending moment or dynamic load. Secondly, complicated manufacturing processes including special curing techniques, high energy compaction and difficulty in material supply have prevented the global-wide adoption of UHSC. Thirdly, numerous UHSC mix designs have been proposed in the literature but they are considerably pricey according to the previous cost-benefit analysis.[17,18] This is because they consisted of many significantly expensive raw materials such as supplementary cementitious materials, specially graded aggregates, high range water reducers and fibrous materials. To solve these research gaps, the study introduces an experimental investigation of economical ultra-high strength concrete involving different types of micro steel fibres. The examined fibres had a very small fibre geometry up to a length of 6 mm and a diameter of 0.12 mm which was much lower than those presented in the literature. On the other hand, the proposed mix design was proved to be cost-effective due to comprising an optimised proportion of traditional raw materials. It required a normal curing technique with water at ambient temperature and no high energy compaction method considered as a simple manufacturing solution. The addition of fibrous materials was supposed to control the brittleness of the proposed economical UHSC so that extending its practicality. The cost evaluation conducted in this study also indicated the cost advantage of this fibre-reinforced UHSC.

2 EXPERIMENTAL SETUP

2.1 Raw materials

To investigate the influence of micro steel fibres on concrete performance and ensure the accuracy of test results, all concrete batches were based on a mix design composed of an identical proportion of cement, silica fume, fine aggregate, water and water-reducing admixture, as shown in Table 1. The variations in the batches were fibre types and contents. In this experiment, cement was a general-purpose type satisfying the specification of AS/NZS 3972.[67] Silica fume was the only supplementary cementitious material used in this concrete mix. This ultrafine material conformed to the requirement of AS/NZS 3582.3.[68] In concrete with compressive strength exceeding 100 MPa, the dosage of silica fume varied in a very wide range and could be up to 40% of cement weight.[13] In a vast body of literature, numerous researchers applied a silica fume to cement weight ratio between 0.10 to 0.30 to manufacture UHSC from grade 120 to 180.[6,14,46,69,70] The amount of supplementary cementitious material was one-fourth of the cement content in the proposed mixture.

Natural sand was used as the only aggregate presented in this mix design because concrete without coarse aggregate was believed to improve the strength of UHSC.[11] Fine aggregate has a greatly smaller particle size than that of other coarse aggregates so that increases the homogeneity and uniformity of internal concrete structure. The mix design contained the same amount of aggregate and cement or the aggregate-to-cement ratio was 1.00 based on the original mix proportion of Sobuz et al.[6]

To increase the compressive strength of concrete, the proposed mix design limited the use of water in which the applied water-to-binder (*w/b*) ratio was only 15%. Under a very low water content, fresh mixture would show such a significantly large viscosity that have a negative effect on the performance of hardened concrete because they have difficulty releasing air voids or bubbles inside their inner structure during the compaction process. Especially, this poor performance concrete would be not suitable to apply to high rise building constructions where require fresh mixture to be highly pumpable. In this study, MasterGlenium SKY 8379, a water reducer admixture, was chosen to improve the workability of fresh concrete.

2.2 Micro steel fibre

Five different types of fibres including three straight and two hooked-ended steel fibres were examined in this experiment. They were ST50, ST65, ST108, HE75 and HE125, in which ST and HE stand for straight and hooked-ended types, respectively and the subsequent number is the aspect ratio of fibre. They were manufactured from very high strength steel with a tensile capacity of 2850 MPa. The appearance of steel fibres used in this experiment was shown in Figure 1 and their detailed dimensions were indicated in Table 2.

2.3 Testing procedure

Three different tests including slump flow test conforming to ASTM C1611,[71] compressive strength test satisfying ASTM C39[72] and splitting tensile strength test by ASTM C496[73] were to investigate the effect of different types of micro steel fibre on the mechanical properties of fresh and hardened UHSC. They were conducted by a 3,000 kN compression testing machine. To prevent samples from sudden destruction due to the brittleness of UHSC and easily capture the post-peak response of test specimens, the machine was operated with displacement controlled loading at a slow rate.

The key content of the mixing process was shown in Table 3. This work could be also found in many previous studies[46,54,61,74] reporting the manufacturing of fibre-reinforced concrete. A 50-litre capacity pan mixer used in this experiment have a very great operating power which was suitable to mix high consistency concrete. The dry materials including binder and aggregate were first added to the pan and performed dry mixing for two minutes. The rotational speed at this stage was at a low rate to prevent very fine material from dispersing out. At the break time, the compound should be carefully checked its uniformity because a considerable amount of silica fume probably stuck on the corner of the pan and affected the concrete proportion. As the dry compound was well combined, water and superplasticizer were added to the running mixer. In this stage, the workability of the mixture steadily increased with time. The duration of wet mixing was 15 minutes at a high rotational speed. The fresh concrete achieved its best performance when showing an unvaried flowability regardless of increasing mixing time. Finally, steel fibres were added to the pan and mixed with fresh concrete for four minutes.

After the mixing process, a slump flow test was carried out to examine the flowability of the fresh mixture. Then, concrete was cast in moulds to form 75x150 mm cylinder samples. A set of four identical specimens were made and evenly shared for both compressive and tensile strength tests. The final result of each test was the mean value of two tested cylinders. They were left in their moulds for progressively hardening and taken off on the day after. In this experiment, concrete samples were soaked in water at ambient temperature. Required no special curing technique such as hot water or steam and high pressure, this simple curing method could make the proposed mix design to be easily and widely applied in practice. Moreover, due to the high brittleness of UHSC, any imperfection on the cylinder ends where loading plates directly contacted would lead to an unexpected fracture behaviour. To ensure the precision of test results, all concrete cylinders were evened out the two ends by a grinding machine before testing, as shown in Figure 3.

3 TEST RESULTS

3.1 Properties of fresh concrete

Table 4 shows the results of flowability, compressive, tensile strength and ductility of concrete involving different types of steel fibres. While other tests were carried out on specimens at 28 curing days, a slump flow test was done immediately after mixing concrete. The value of workability was the average of two perpendicular diameters measured from fresh mixture flowing on a base plate.

The proposed non-fibre mix design provided an excellently workable concrete with a slump flow value of 702.5 mm. Increasing the dosage of steel fibre, the flowability of concrete reduced accordingly. This phenomenon was well-documented in many existing studies[8,55,75,76] which investigated the performance of concrete incorporating various fibre volume fractions. Among the V_f = 0.5% mixture, the workability of concrete varied in a wide range from 492.5 mm to 615.0 mm. On the other hand, by adding 1.0% more fibre volume fraction, wet concrete tended to lose a slump flow value of 106 mm or 20% of flowability.

Between the two types of fibre, the mixture having hooked end fibres indicated a better performance in flowability than that of straight fibre concrete. The average slump values of concrete with hooked end fibres were 601.3 mm and 497.5 mm while straight fibres provided mean values of 499.3 mm and 391.7 mm for fibre volume of 0.5% and 1.5%, respectively. Incorporated 0.5% of hooked end fibres, concrete still gained reinforcement and achieved up to 85% of the flowability of the non-fibre mixture.

Besides the pumping capacity, the workability of fresh mixture also had a significant influence on the ability to release entrapped air bubbles from concrete structures. Due to the lower value of slump flow, V_f = 1.5% specimens presented a greater number of air voids than that of V_f = 0.5% specimens, as shown in Figure 4. This behaviour definitely decreased the UHSC uniformity and caused a reduction in their mechanical performance.

3.2 Failure modes

Figure 5 indicates the failure patterns of fibre-reinforced concrete cylinders under compressive strength tests. There were two modes including cone and shear fractures which were specificated by ASTM C39[72]. It was observed that all specimens exhibited no physical damage to both ends of cylinders after testing. As cracks did not form a columnar pattern through cylinder ends or a minor side fracture, the inner structure of concrete specimens was in a well-formed and homogeneous condition. Unlike what happened to non-fibre concrete, fibre-reinforced specimens presented no explosive failure in which concrete was crushed into small pieces right after reaching their ultimate loading, but still remained their cylindrical shape. The absence of explosive mode indicated the effectiveness of fibres on bridging and controlling concrete crack development.

As added steel fibres, the formation of cracks on the surface of tested cylinders differed from that of unreinforced concrete as shown in Figure 6. While the surface of non-fibre concrete introduced cracks with sharp edges, fibre-reinforced samples fractured in an edgeless pattern under axial loading. Moreover, a fewer number of separated fragments with a large size were observed in these specimens involving fibrous materials formed during their post-cracking stage. These behaviours demonstrated the ability of fibre bridging to reduce the stress intensity around the area of cracks.

During the compressive strength test, the loading machine operated by a displacement control to obtain the strain-softening behaviour of fibre-reinforced concrete. However, this behaviour was not always properly captured by the data logger because of the high brittle property of UHSC. In this experiment, several specimens in which most of them contained V_f = 0.5% were failed without post-peak deformation. This performance resembled what plain UHSC behaved under axial loading. This type of brittle concrete tended to abruptly fracture as soon as they achieved their maximum stress following a snapping noise.

3.3 Effect of micro steel fibre on compressive strength

At V_f of 0.5%, all fibre-reinforced specimens indicated a similar compressive capacity which was from 135.1 MPa to 144.2 MPa, as shown in Table 4. It was noticed from these test results that no specimen exceeded the compressive strength of non-fibre concrete. The strength reduction could be explained by the poorer workability of $V_f = 0.5\%$ UHSC which increased the air content in the inner concrete structure. Under a low flowability, it was more difficult for fresh mixture to release air bubbles during the compaction process.[54] As a result, this phenomenon had a negative impact on the loading capacity of UHSC samples consisting of fibres.

Meanwhile, at a volume fraction of 1.5% fibre, the maximum value of strength that a fibre-reinforced specimen could achieve in this experiment was 157.6 MPa. Specimens with HE125 and HE75 exhibited a better compressive capacity than that of concrete containing straight fibres. The average difference in compressive strength between hooked end and straight types was 12%. As reported in many previous studies, straight fibres possessed a poorer performance in crack bridging than that of other shaped fibres due to a lower pull-out capacity.[40,66] Therefore, having more content of hooked end fibres in mixture could slightly increase the compressive capacity of UHSC.

In general, micro steel fibres had an insignificant effect on the compressive strength of UHSC. This mechanical property was also not the major target when it came to adding fibrous materials to concrete. However, the quality of fresh concrete with low content of micro steel fibres should be carefully considered along with their compressive strength since two of them were in agreement with each other.

3.4 Effect of micro steel fibre on tensile strength

According to Denneman et al.,[33] the splitting tensile test was an indirect and uncomplicated method but still approximately captured the tensile strength of UHSC specimens with steel fibre. Figure 7 indicates a typical load-displacement response of fibre-reinforced UHSC. Normally, the tensile strength was determined by the maximum load P_u in the tensile test. However, this was not the case in fibre-reinforced concrete due to their characteristic behaviour in which their ultimate load was not at the linear elastic region but in the plastic regime. Moreover, it was noticed from the splitting tensile test that the first cracking happened at the elastic limit while the maximum load P_u was the representative of secondary cracking. Hence, to precisely estimate the tensile strength of a fibre-reinforced concrete, the load at the first cracking P_t in the load-displacement curve should be considered instead of the maximum load P_u.

In general, the increase of fibre content in concrete led to the improvement of tensile strength. Containing 0.5% fibre volume, the tensile strength of tested concrete gained 4% to 55% compared to the non-fibre specimen in which the maximum strength of 13.2 MPa was of the specimen containing hooked end steel fibre with an aspect ratio of 125 (HE125). On the other hand, the tensile capacity of concrete with V_f = 1.5% was significantly increased from 65% to 145% in comparison to concrete without fibre. The greatest value obtained from splitting cylinder tests again belonged to samples of HE125 with tensile capacity up to 20.8 MPa.

In the same group of fibres, there was a tendency that the tensile strength of UHSC could be improved regarding the aspect ratio of steel fibres. Despite the difference in length and diameter, both ST65 and ST50 offered a similar tensile performance for UHSC, especially for mixes with a fibre volume of 1.5%. This is because of their proximate aspect ratios in which ST65 and ST50 had *L/D* ratios of 65 and 50, respectively. On the other hand, by substituting ST108 for ST50 in the mix design, concrete specimens increased up to 20% tensile strength. A comparable case was observed in the group of hooked end fibre when specimens with HE125 also performed better in splitting test than concrete containing HE75. Hence, it can be said that micro steel fibre with a greater aspect ratio could effectively enhance the tensile strength of UHSC. A similar finding was also reported in the study of Aydın and Baradan[77] where the increase in fibre length had a positive effect on the fibre-matrix bond capacity at cracking points.

3.5 Effect of micro steel fibre on ductility

Cohn and Bartlett[78] suggested a method to determine the ductility index (μ_Δ) of structural members based on their load-displacement response, as shown in Figure 9. This displacement ductility index was defined by the ratio of the displacement at the 85% of the peak load on the strain-softening behaviour (Δ_1) to the displacement corresponding to idealized yield displacement (Δ_2) as Equation (1):

$$\mu_\Delta = \frac{\Delta_2}{\Delta_1} \tag{1}$$

The idealized yield displacement in the elastic range was obtained by regression analysis. According to this definition, a sample with a higher ductility index performed a better ductility capacity. In the experiment of this study, the ductility index of UHSC in this study was calculated from the compressive strength test results. Due to the typical behaviour of UHSC in which concrete specimens tended to perform an approximately linear load-displacement or stress-strain response in the elastic phase, the idealized yield displacement of these specimens could be simply and precisely captured.

A ductility improvement was observed in all concrete samples involving V_f = 1.5% where their index values varied from 1.23 to 1.33. However, the performance of ductility was various in regards to the shape of fibres. Among the tested specimens, a volume fraction of 1.5% HE75 or HE125 conducted a better ductile performance to UHSC than that of straight fibres, as shown in Figure 8(e) and (f). This phenomenon could be explained by the ability of deformed steel fibres to more effectively govern the crack propagation in concrete. Figure 10 indicates different stages of materials under axial load reported by Schultz.[79] These stages were void closing, elastic response, microcracks forming, cracks linking and fracture in the order of appearance in the stress-strain curve. Due to the limited number of air voids in the internal structure of UHSC, the stage of pore closing may not be available at first so that only elastic range and microcracks engaged in the pre-peak response, as shown in Figure 8. Steel fibres played an important role in the microcracking formation stage so that improved the tensile strength of concrete, as shown in the result of the splitting test. On the other hand, in the compressive strength, they also presented a significant effect on the post-peak performance test when concrete cracks were expanding. Moreover, regarding the definition of displacement ductility index, 85% of the peak load on the strain-softening behaviour of the tested specimens mostly at the cracks linkage stage. Hence, if a fibrous material effectively controlled and minimised the generation and propagation of cracks, there was a high chance that it also increased the value of the ductility index for concrete.

As reported by Ibrahim et al.,[80] a fibre with a higher aspect ratio had a positive impact on delaying cracks from propagating in a concrete structure. This comment was also accurate to micro steel fibres where the length of cracks linkage stage from the stress-strain curves reduced in the sequence ST50, ST65, ST108, HE75 and HE125 specimens, as shown in Figure 8. As a result, UHSC could obtain a better ductile performance in accordance with the increase of aspect ratio of fibres.

Regarding the microcrack stage, two values which should be taken into account were the microcracks launching strain and the strain at the peak stress or the end of microcrack stage. The strains in which microcracks stage begun were 0.0025, 0.0027, 0.0032, 0.0038 and 0.0042 in ST50, ST65, ST108, HE75 and HE125 specimens with V_f = 1.5%, respectively. However, it has been believed that at the same V_f, a greater number of fibres which was small in size could command the growth of microcracks more effectively.[63] In other words, the extent of the microcracks stage tended to last longer in the stress-strain response of concrete containing smaller fibres, as shown in Figure 8. Accordingly, these fibres were also expected to provide better compressive performance for UHSC. But it was not true in the tested specimens of this study where the end of their microcracks stage appeared in a contrasting manner. The strains at the peak stress were 0.0039, 0.0041, 0.0043, 0.0046 and 0.0049 in ST50, ST65, ST108, HE75 and HE125 specimens with V_f = 1.5%, respectively. It should be noted that non-fibre concrete had an approximately linear stress-strain response under compressive strength test and entirely fractured at the strain of 0.0042. Therefore, despite the advantage of low aspect ratio fibres (ST50 and ST65) beneficially controlling the growth of microcracks, they offered a poorer overall performance when crushing at earlier strain than that of non-fibre specimens.

Among specimens with V_f = 0.5%, there were several null values in the ductility index column in Table 4 including the results of specimens consisting of ST65, ST108 and HE75. This was because these specimens presented no strain-softening behaviour or no post-peak response in the stress-strain curve, as shown in Figure 8(c), (d) and (e). This behaviour was also observed in the compressive strength test of non-fibre specimens with high brittleness. Consequently, it could be said that adding micro fibres ST65, ST108 and HE75 with a volume fraction of 0.5% made no improvement to the ductile performance of the proposed concrete mix. On the other hand, specimens containing ST50 and HE125 at V_f = 0.5% posted a ductility index of 1.20 and 1.17, respectively. In addition, they both had a strain at the peak stress of 0.0043 which was slightly greater than that of plain concrete. However, specimens with V_f = 0.5% ST50 performed poorly in the splitting test as ST50 inconsiderably increased their tensile capacity, so HE125 would be the better solution for fibre-reinforced concrete.

Since fibrous materials have been widely described as a very pricey component.,[81] reinforced concrete could considerably enlarge the construction budget when applying a high content of fibre. However, even at a very low dosage, concrete still benefited from fibre in improving the tensile strength and ductility, reducing the brittleness and introducing the post-peak behaviour. So adding a fibre volume by 0.5%, the proposed UHSC mix could not only make an improvement in ductile performance but also ensure its cost-saving benefit.

4 EVALUATION OF MATERIAL COST

4.1 Properties of fresh concrete

The unit price of concrete constituents including cement, substitute cementitious materials, aggregates, high range water reducer and micro steel fibre were collected from previous studies and material supplies. In the study of Isa et al.,[82] cement, silica fume, natural sand, and coarse aggregate costed 309, 1092, 328, and 364 AUD per ton, respectively. Australian Builders provided ground slag at 850 AUD per ton and Domcrete supplied specially graded aggregates at 750 AUD per ton. The most expensive component in UHSC mix was a superplasticizer from Sika Australia Pty Ltd with a price of 5460 AUD per ton. Micro steel fibre manufactured by Ganzhou Daye Metallic Fibres Co., Ltd was rated at 2940 AUD per ton. It should be noted that the price per weight of raw materials in this study was the retail price and involved no freight charge. In practice, material costs might be varied from project to project depending on dozens of factors. However, the cost evaluation in this study could provide a frame of reference for how different dosages of steel fibres affect the overall material cost of UHSC.

4.2 Cost of concrete mix

In literature, many research experimentally explored the effect of different dosages of steel fibre on the mechanical properties of concrete. A very high content of steel fibre up to 5% by volume reported by Kazemi and Lubell[83] and Meng and Khayat.[66] or 6% by volume in the studies of Pourbaba et al.,[65] Abbas et al.,[8] and Nehdi et al.[56] Nevertheless, any fibre dosage exceeding 5% by volume tended to have a negative impact on the economic aspect of concrete, so this value was selected as the upper limit in this cost evaluation.

Table 5 and Figure 11 presented a cost estimation of several existing mix designs[8,17,51,66,84-86] based on their components. The contribution of steel fibre to the total expense of concrete varied in a very wide range which was from 6% to 106% of non-fibre concrete costs. A volume of 5% steel fibre in mix S5.0 was approximately comparable to the sum of cement, substitute cementitious materials, aggregate, and superplasticizer in its mixture.

In general, a high content of fibres was in accordance with an increase in the price of mixture where an addition of fibre by 0.5% volume would build up approximately 7% to the material cost. Among mix designs with the same dosage of fibre, the proposed concrete was always the most cost-saving solution. This economical mixture could save material budget by around 26% compared to existing mix designs with the same content of fibre.

Concrete can benefit from a high dosage of fibre by adding resistance to cracking, reducing the effect of brittleness, and improving tensile strength and ductility. Despite these advantages, the selection of fibre volume should be considered carefully not only in terms of mechanic properties of concrete but also in terms of economy. According to the cost evaluation, steel fibres played an important role in a construction budget where a high volume of fibrous material might double the worth of concrete. Therefore, to ensure the affordability of the economical concrete proposed in this study, no fibre volume exceeding 1.5% was experimentally investigated.

5 CONCLUSIONS

The study provided an experimental investigation on the effect of micro steel fibres including ST50, ST65, ST108, HE75 and HE125 at different volume fractions on UHSC. The prime aim was to improve the ductility of the economical UHSC mix design which used traditional raw materials and ease of manufacturing. Micro steel fibres with a length of 6 mm to 25 mm and a diameter of 0.12 mm to 0.20 mm were used because they were believed to provide a better homogeneity for UHSC than normal steel fibres. The finding of this study was based on the comparison of the mechanical performance between concrete with and without fibre from several tests.

Regarding the slump flow test, concrete with fibres had poorer workability than that of mixture without fibres, as well-documented in the literature, with a reduction of 12% to 47% in flowability.

Concerning the compressive and splitting tensile strength test, the application of micro steel fibre might have little influence on the compressive capacity but could significantly enhance the tensile performance of UHSC. The improvement was up to 55% and 145% compared to non-fibre concrete when adding a volume fraction of 0.5% and 1.5% HE125, respectively.

The tensile capacity of UHSC also increased in accordance with the increase of the fibre aspect ratio. Substituting ST108 for ST50 or HE125 for HE75 in the proposed concrete mix could provide an improvement in tension by 20%.

Applied a low fibre content as $V_f = 0.5\%$, the proposed UHSC mix remained a cost-effective solution for constructions. Among the specimens with $V_f = 0.5\%$, the concrete reinforced by HE125 provided the best improvement with a ductility index of 1.17 and tensile strength of 13.2 MPa.

According to the cost evaluation, the concrete proposed in this study was the lowest-budget mix design where it was priced around 26% less than existing mixes at the same dosage of fibre. Moreover, each fibre volume by 0.5% increased the total cost of concrete by approximately 7%. Hence, a low content of steel fibre should be applied to reinforced concrete to keep construction on budget.

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Table Captions

Table 1: Concrete mix

Table 2: Steel fiber properties

Table 3: Mixing process

Table 4: Test results

Table 5: Estimated material cost

Table 1: Concrete mix

Materials	Relative weight ratio to cement
Cement	1.00
Silica fume	0.25
Sand	1.00
Water	0.181
Superplasticizer	0.023
Steel fibre	0.5% or 1.5% by total volume of mixture

Table 2: Steel fiber properties

Type	Steel fibre	L (mm)	D (mm)	Aspect ratio
Straight	ST50	6	0.12	50
	ST65	13	0.20	65
	ST108	13	0.12	108
Hooked-ended	HE75	15	0.20	75
	HE125	25	0.20	125

Table 3: Mixing process

Process	Duration	Note
Adding raw materials	-	Make sure mixer pan clean and dry
Mixing	2 min	Well combined dry materials
Break	2 min	
Adding water and superplasticizer	-	
Mixing	15 min	Until presenting a flowable mixture
Adding steel fibres	-	
Final mixing	4 min	

Table 4: Test results

Type	Steel fibre	V_f %	Slump (mm)	Compressive strength (MPa)	Splitting tensile strength (MPa)	Ducility index
Straight	ST50	0.5%	505.0	141.4	8.8	1.20
		1.5%	395.0	**132.3**	14.0	1.23
	ST65	0.5%	500.5	136.0	10.5	-
		1.5%	375.0	132.8	14.4	1.25
	ST108	0.5%	492.5	144.2	11.3	-
		1.5%	405.0	141.1	17.0	1.29
Hooked-ended	HE75	0.5%	615.0	141.7	11.6	-
		1.5%	535.0	145.4	17.3	**1.33**
	HE125	0.5%	587.5	135.1	13.2	1.17
		1.5%	460.0	**157.6**	**20.8**	1.31
Non-fibre		0	702.5	144.2	**8.5**	**-**

Table 5: Estimated material cost

Reference	Mix	C:SCM:Agg	SP %	V_f %	Plain concrete cost (AUD/m^3)	Total cost (AUD/m^3)
Chkheiwer et al.[51]	M1	1:0.25:1.00	6.0	-	1666	1666
	M2			0.5	1657	1772
	M3			1.0	1649	1878
	M4			1.5	1641	1985
	M5			2.0	1632	2091
Abbas et al.[8]	M6	1:0.20:1.50	3.5	-	1456	1456
	M7			1.0	1425	1654
	M8			3.0	1364	2051
Meng and Khayat[66]	M9	1:0.69:1.47	0.9	-	2097	2097
	M10	1:0.69:1.47	1.0	1.0	2096	2325
	M11	1:0.62:1.44	1.1	2.0	2095	2554
	M12	1:0.69:1.47	2.9	3.0	2300	2988
	M13	1:0.69:1.47	3.4	4.0	2358	3276
	M14	1:0.69:1.47	4.6	5.0	2490	3637
Park et al.[87]	M15	1:0.25:1.40	6.7	-	1860	1860
	M16			0.5	1851	1965
	M17			1.0	1841	2071
	M18			1.5	1832	2176
Wang and Gao.[85]	M19	1:0.30:1.10	1.8	-	1362	1362
	M20		2.1	1.0	1381	1610
	M21		2.3	2.0	1399	1858
	M22		2.6	3.0	1416	2104
Bae et al.[86]	M23	1:0.25:1.40	1.3	0.0	1252	1252
	M24			0.5	1246	1360
	M25			1.0	1239	1469
	M26			2.0	1227	1686
This study	S0	1:0.25:1.00	2.3	-	1135	1135
	S0.5			0.5	1130	1244
	S1.0			1.0	1124	1353
	S1.5			1.5	1118	1462
	S2.0			2.0	1113	1571
	S3.0			3.0	1101	1789
	S4.0			4.0	1090	2007
	S5.0			5.0	1078	2225

Note: C, SCM, Agg and SP are the ratios by weight of cement, substitute cementitious materials, aggregate, and superplasticizer to the weight of cement.

Figure Captions

Figure 1 Steel fibres

Figure 2 Comparison of steel fibre distribution on the top surface of concrete cylinders

Figure 3 Grinding concrete cylinders

Figure 4 Comparison of air voids on the surface of typical samples with volume of 0.5% and 1.5% steel fibres

Figure 5 Failure modes of concrete cylinders with steel fibres

Figure 6 Cracks on concrete cylinders with and without steel fibres

Figure 7 Typical splitting tensile test result

Figure 8 Compressive strength test results

Figure 9 Displacement–ductility parameters

Figure 10 Different stages in stress-strain response of concrete under axial load

Figure 11 Material costs of several mix designs

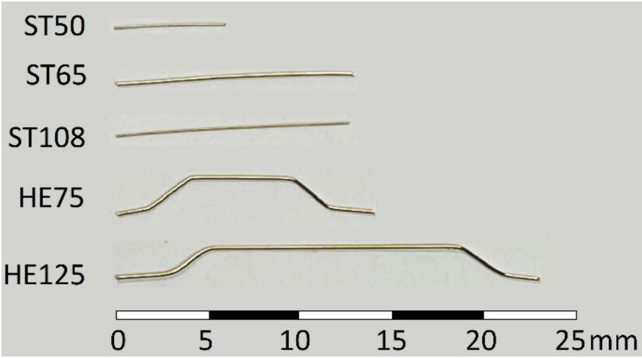
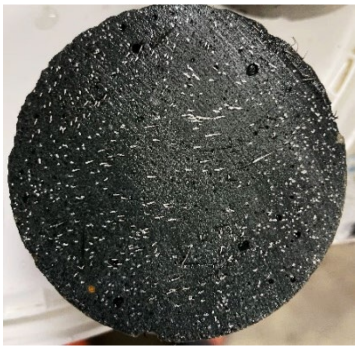


Figure 1 Steel fibres

(a) $V_f = 0.5\%$



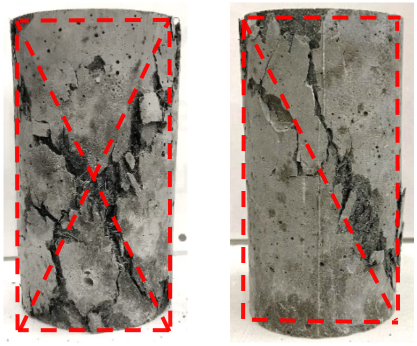
(b) $V_f = 1.5\%$

Figure 2 Comparison of steel fibre distribution on the top surface of concrete cylinders

(a) Grinding machine (b) Before (c) After

Figure 3 Grinding concrete cylinders

Figure 4 Comparison of air voids on the surface of typical samples with volume of 0.5% and 1.5% steel fibres



(a) Cone (b) Shear

Figure 5 Failure modes of concrete cylinders with steel fibres

(a) Non-fibre concrete (b) Concrete with fibres

Figure 6 Cracks on concrete cylinders with and without steel fibres

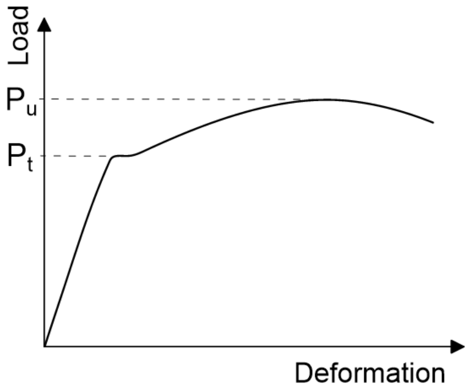


Figure 7 Typical splitting tensile test result

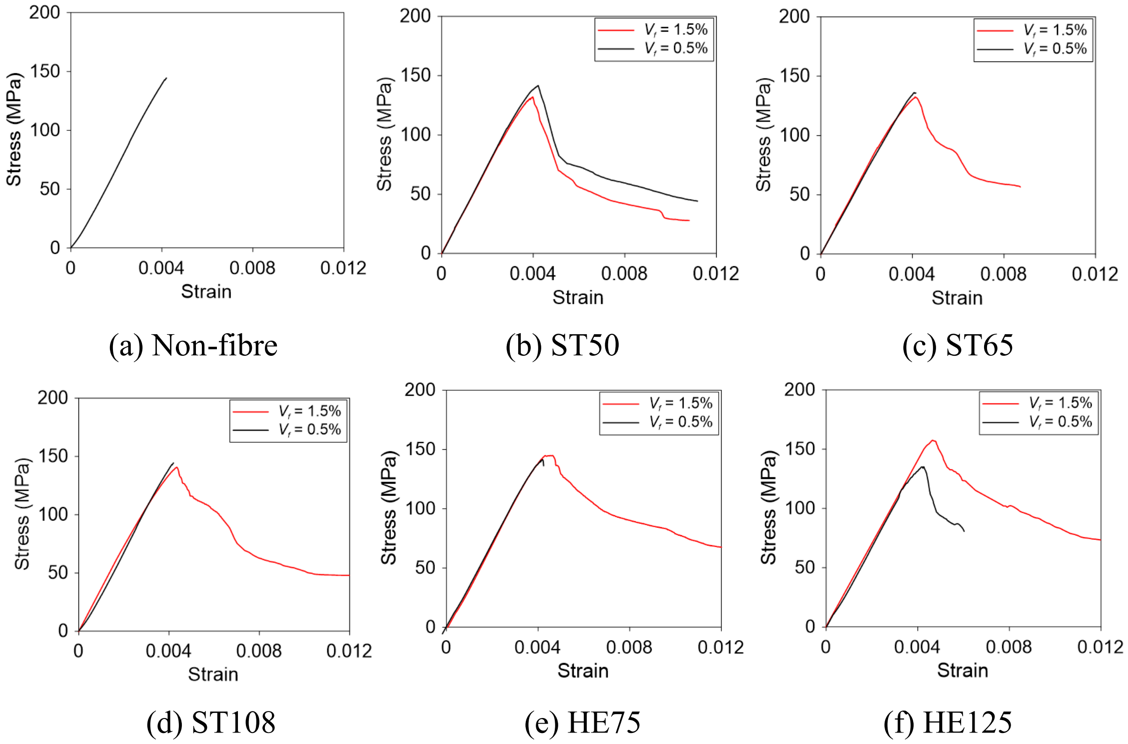


Figure 8 Compressive strength test results

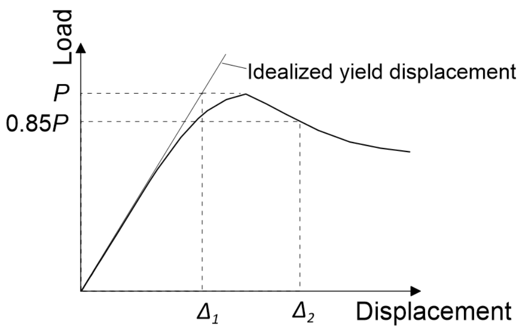


Figure 9 Displacement–ductility parameters

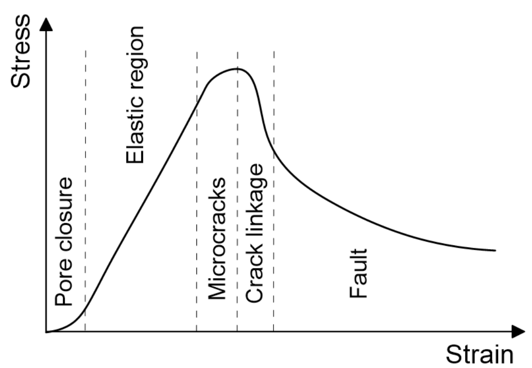


Figure 10 Different stages in stress-strain response of concrete under axial load

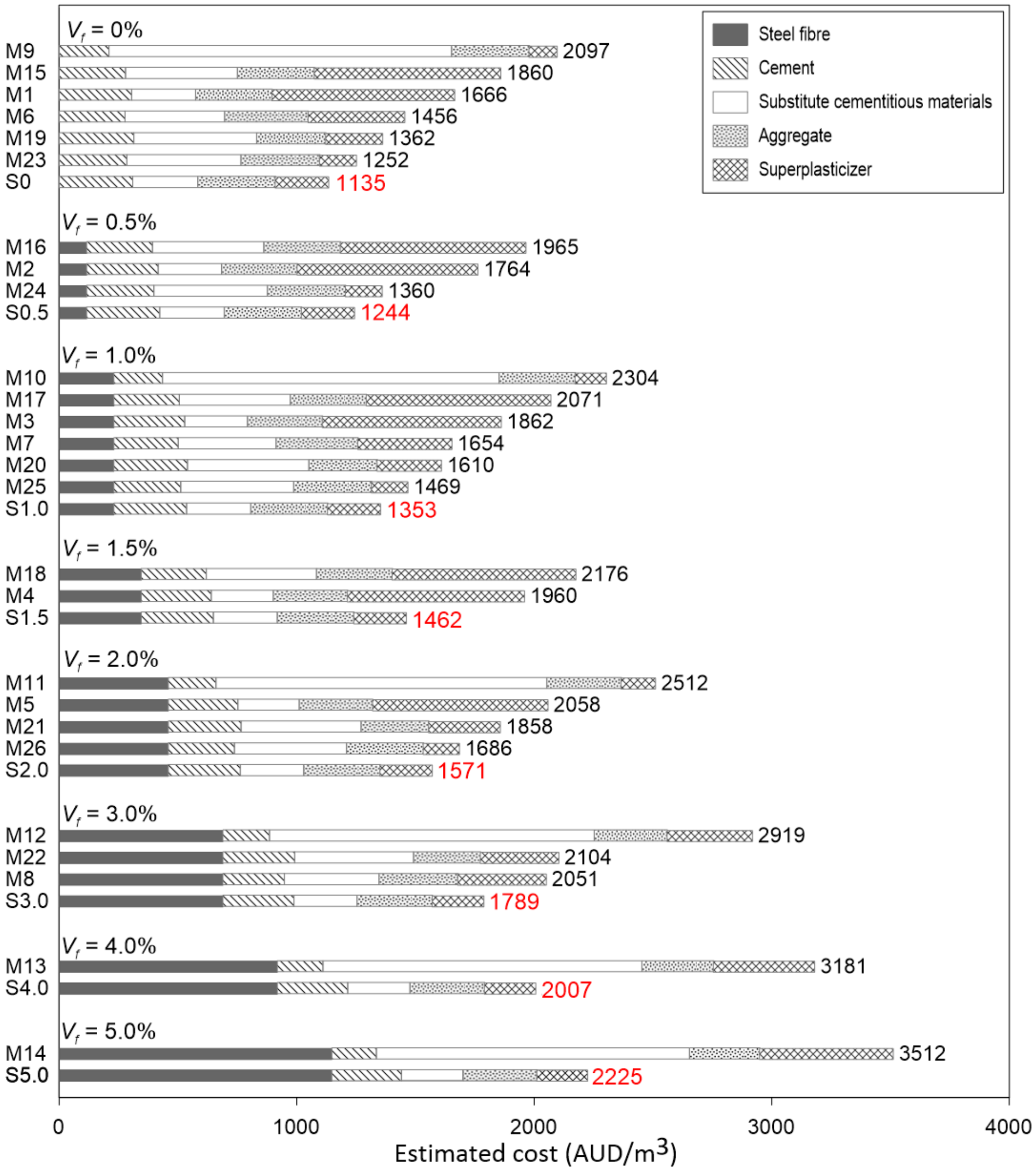
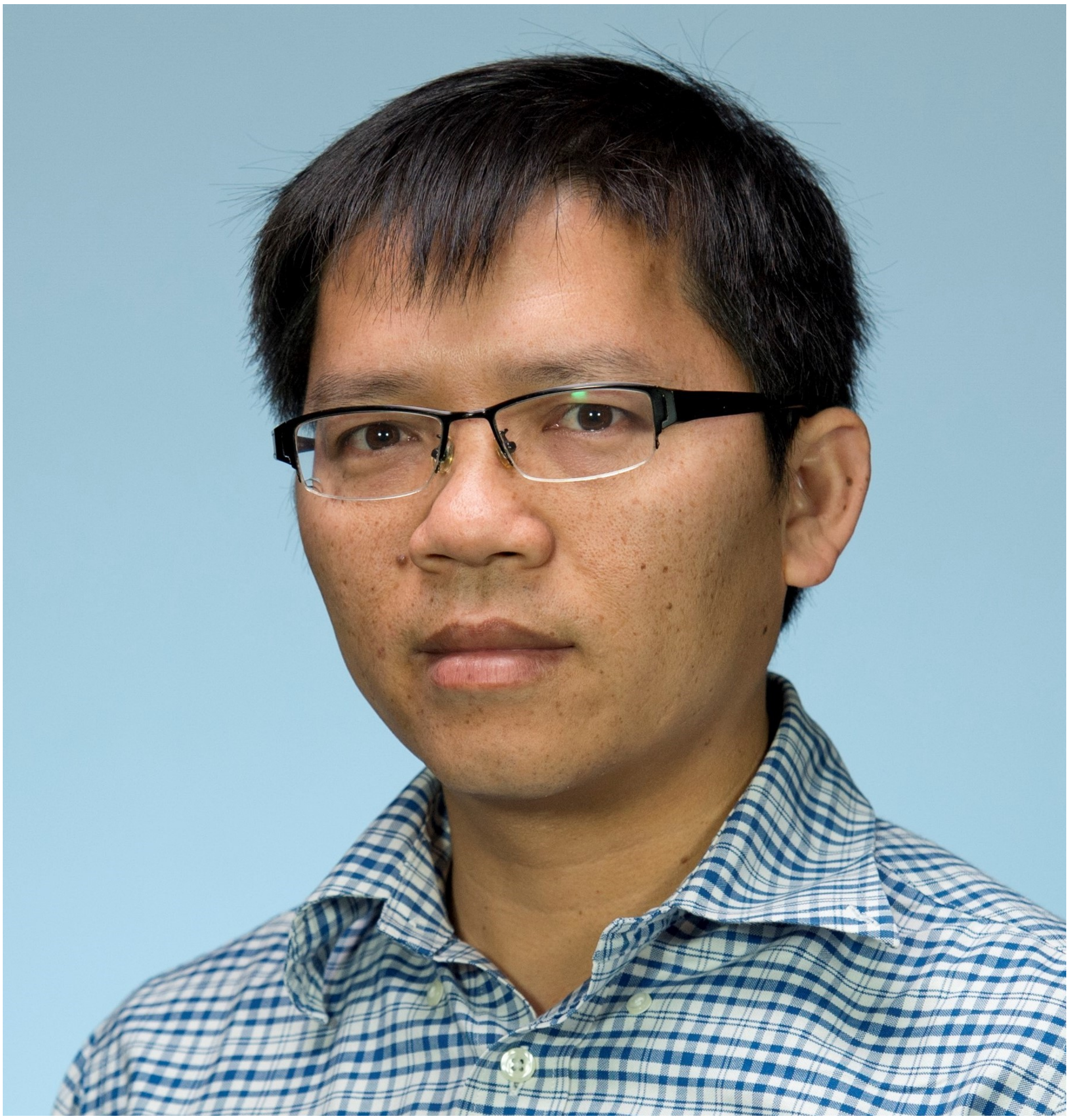


Figure 11 Material costs of several mix designs



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