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Reduction in cement content of normal strength concrete with used engine oil (UEO) as chemical admixture

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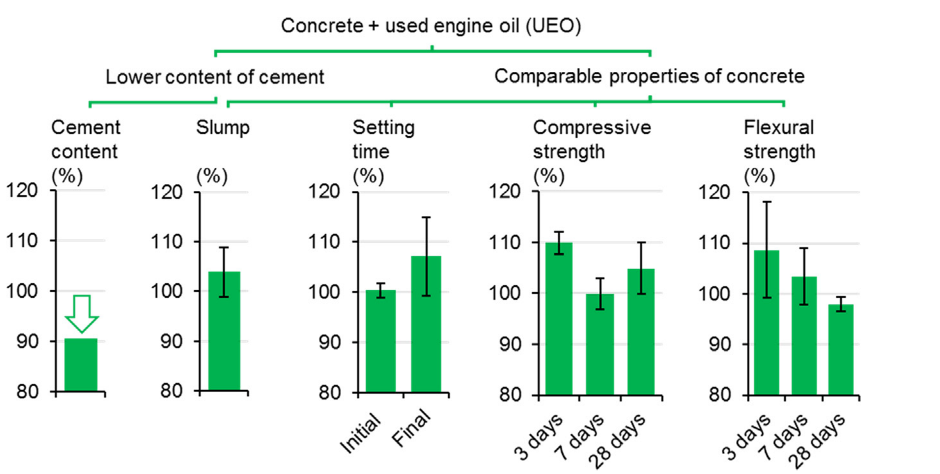
HIGHLIGHTS

- Used engine oil (UEO) was used as chemical admixture for normal strength concrete.
- UEO largely complied with ASTM C494 type A water-reducing admixture.
- Water-reducing and air-entraining features of UEO facilitated less cement content.

GRAPHICAL ABSTRACT



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ABSTRACT

In this study, the coupling effects of admixing a used engine oil (UEO) and reducing the cement paste content on the properties of a normal strength concrete were investigated. Initially, various tests were performed to determine the effect of the admixed UEO on the properties (*i.e.* workability, air content, setting times, strengths, drying shrinkage, and freezing and thawing (F–T) durability) of the reference concrete (formed in accordance with ASTM C494). Based on the acquired knowledge regarding the aforementioned effects, the chemical-admixture type of the UEO was evaluated. The UEO largely complies with the ASTM C494 type A water-reducing admixture specifications. The admixed UEO can facilitate the production of concrete with 9.4% less cement content than that in the reference concrete, but with comparable properties. This study provides a basis for realizing a more economical and eco-friendly production of concrete by both reducing its cement content and admixing UEO.

1. Introduction

The construction of buildings and infrastructure plays a primary role in this urbanization and industrialization era by creating living and working spaces as well as by contributing to national econo-

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mies [1,2]. However, construction activities, such as the production of the associated building materials, can have a significant adverse ecological effect [3]. Portland cement concrete is the most extensively used construction material. The utilization of concrete as a major construction material is expected to continue for the foreseeable future [4]. Compared with other materials, concrete is considered to be more cost-effective and ecological friendlier per unit quantity [5]. However, owing to the large consumption of concrete, the contribution of concrete to the global carbon footprint is significant [6]. The carbon footprint of concrete originates primarily from the use of cement, one of the main components of which is clinker [7]. Concrete production releases an equivalent carbon dioxide (CO_2eq) that is approximately equal to the CO_2eq for clinker production. Furthermore, it requires a large amount of energy during the sintering process [8,9].

To reduce the adverse ecological effects caused by the large concrete production, different efforts have been attempted. They mainly include minimization of the cement content by incorporating mineral and chemical admixtures [10–12]. The coupling effect of admixing mineral and chemical admixtures is used to tune the properties of concrete to reach the desired targets [13,14]. Various mineral admixtures formed from waste and industrial by-products have been extensively studied and successfully implemented in the field application of concrete [15–17]. Concurrently, studies on waste utilization to generate alternatives for chemical admixtures are still limited. One of the waste materials that has been explored for its potential function as a chemical admixture is used engine oil (UEO).

Admixed UEOs are reported to affect the fresh (*i.e.* prior to the initial setting time) and hardened properties of normal strength concrete. The workability and air content of fresh concrete with an admixed UEO are higher than those of the plain reference concrete [18,19]. In comparison, the final setting time of concrete is decreased on admixing [20]. The mechanical properties (*i.e.* compressive strength, flexural strength, splitting tensile strength, and modulus of elasticity) of a hardened concrete with admixed UEO decrease [18,19,21–23]. A 5% reduction in the water content (e.g., change in the water to cement ratio from 0.62 to 0.59) was reported to result in comparable workability and mechanical properties of the concretes [18]. A study on the structural behavior of a beam demonstrated that admixing of a UEO adversely affects the ultimate flexural capacity, maximum shear load, and bond splitting resistance of the reinforced concrete beam [24]. Additionally, it has been suggested that the leakage of oil into cement during its grinding process can result in concrete with relatively higher resistance to freezing and thawing (F–T) than that without oil [25].

Several features of UEOs serving as chemical admixtures have been revealed in previous studies. However, there is still a gap between the results of laboratory investigations and the commonly employed information for the field applications of chemical admixtures. For instance, the type of UEO suitable as a chemical admixture is yet to be investigated. The knowledge of the type of the chemical admixture is important to match it with the concrete class such that its use is beneficial to the concrete. A common practice in the tendering process of chemical admixture procurement is the provision of the specification of its type (*i.e.* A, B, C, D, E, F, or G as defined in ASTM C494 "Standard Specification for Chemical Admixtures for Concrete") for a specific class of concrete by a concrete engineer. Based on the information of all the concrete components, their portions are designed to meet the target concrete performance by considering its economic and ecological aspects. Based on the existing literature, it is perceived that admixing a UEO and minimizing the cement content in concrete can reduce its production cost and carbon footprint, which will lead to economic and ecological benefits. However, the basis for the method of admixing a UEO and minimizing the cement content in concrete without adversely affecting its properties is still unknown.

The present study aims to investigate the coupling effects (*i.e.* on normal strength concrete properties) of admixing a UEO and reducing the content of cement paste (CP) in concrete. The reference concrete was formed according to the criteria in ASTM C494 and results in normal strength concrete. Initially, laboratory tests were performed for determining the dosage of the admixed UEO based on its optimum effect on the fresh concrete workability. Subsequently, the effect of the admixed UEO on the fresh concrete workability and air content as well as the mechanical and durability (*i.e.* setting times, compressive and flexural strengths, drying shrinkage, and F–T resistance) properties of the hardened concrete were assessed. Based on these effects of the admixed UEO on the concrete properties, the mixing proportion of the reference concrete was adjusted to study the chemical admixture type of the UEO and determine the coupling effects of admixing the UEO and reducing the CP on the concrete properties. In addition to provide the information on the coupling effects of admixing a UEO and reducing the CP in concrete, the present study also indicates the chemical-admixture type of UEO and its effect on drying shrinkage. The information from present study provide a basis for more economical and ecological concrete production from the reduced cement content (*i.e.* the main source of cost and carbon footprint in concrete production) and recycling of UEO as chemical admixture. Moreover, the chemical-admixture type of UEO (*i.e.* including its effect on the drying shrinkage) provides a more detail guideline towards the field application of UEO as chemical admixture.

2. Materials and method

2.1. Mixture proportion of concrete

Distilled water, type 1 ordinary Portland cement (OPC) according to ASTM C150 "Standard Specification for Portland Cement," and locally available fine and coarse aggregates were used as the basic components to form normal strength concrete. The admixed UEO used in the present study is the used multi-grade and semi-synthetic engine oil of Delo® Gold Ultra SAE 15 W-40. This UEO was collected from electrical generator engine operations. The effect of UEO from synthetic and mineral oil on concrete properties had been investigated in the previous study [20]. Hence, the use of UEO from a semi-synthetic oil can provide an insight on the effect of oil type (*i.e.* on concrete properties) used in the present and previous study. Additionally, the majority operators of modern machines prefer semi-synthetic engine oil with a multi-grade specification [26]. A multi-grade engine oil can be used in all the seasons from winter to summer, and the semi-synthetic nature of engine oil increases its life compared to a petroleum-based oil. Economical consideration is also a factor in using semi-synthetic engine oil. Therefore, the obtained knowledge (related to the use of a UEO as a chemical admixture) from the present study will assist in identifying the preferred type of engine oil to be discarded as a UEO.

Various concrete mix proportions, as listed in Table 1, were designed to investigate the effects of the admixed UEO. The reference concrete mix (mix R) was designed according to the standard mix from ASTM C494 for the chemical admixture type determination. Mix R was designed with a cement content of 307 kg/m^3 and slump of 90 ± 15 mm, as specified in the aforementioned standard. The aggregate composition was designed such that the overall gradation is within the limit of the Tarantula curve (Fig. 1a) and that the cement–aggregate composition is in the desirable area of Shilstone's curve (Fig. 1b). Areas I, II, III, IV, and V in Shilstone's curve are considered to those with concrete characteristics of gap graded,

Table 1
Mix proportions by weight per m^3 of concrete. The fine to coarse aggregate ratio is 0.667. b.v. and b.w. stand for by volume and by weight, respectively. w/c is the water to cement ratio and CP is the content of the cement paste.

Mix code	Mix proportion (kg/m^3)			w/c	Reduction (b.w.)		CP (b.v.)
	Water	Cement	Agg.*		Cement	Water	
R	191	307	1810	0.623	na	na	28.9%
U	191	307	1810	0.623	0%	0%	28.9%
U-W6	180	307	1839	0.586	0%	6%	27.7%
U-W8C2	176	301	1854	0.586	2%	8%	27.2%
U-W11C5	171	292	1874	0.586	5%	11%	26.3%

*Total amount of the aggregates

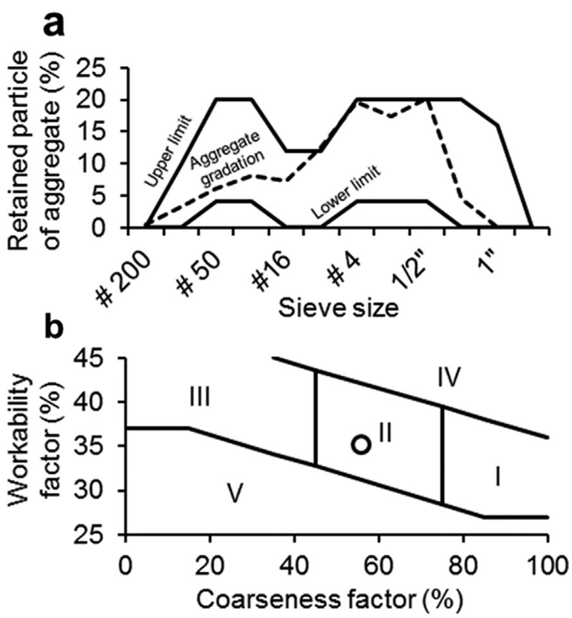

Fig. 1. (a) Tarantula and (b) Shilstone's curves. The aggregate gradation is selected to best fit the limit of the area in the Tarantula curve.

desirable, small top size, sandy sticky, and rocky harsh, respectively. The composition of the concrete used in the present study corresponds to area II, as shown by the circle in Fig. 1b. The development of mix proportions by implementing Tarantula and Shilstone's curves has been documented [27]. The water content of mix R, as listed in Table 1, was determined based on the amount needed to produce a slump of 90 ± 15 mm. The resulting w/c of mix R is similar to that (*i.e.* 0.62) used in a previous study that focused on the effect of an admixed UEO on concrete properties [18].

The investigation of the effects of the admixed UEO were performed on the concrete properties (Mix U), chemical admixture type of the UEO as per ASTM C494 (Mix U-W6), and coupling effects of admixing the UEO and reducing the CP on the concrete properties (Mixes U-W6, U-W8C2, and U-W11C5). The chemical admixture type of the UEO as per ASTM C494 was determined by evaluating the relative change in properties of mix U-W6 from those of mix R with the requirement in ASTM C494. The reduction in the CP (by maintaining the water to cement ratio (w/c)) from mixes U-W6, U-W8C2, to U-W11C5 simultaneously lowers the cement and water contents. The nomenclature for the concrete mixes and the specimens is as follows: R denotes the reference concrete, U denotes a concrete with an admixed UOE, and W and C represent the concrete with reduced water and cement contents compared to those of the reference concrete. The number following W and C denotes the percentage (*i.e.* by weight) of the reduction in the water and cement contents (*i.e.* relative to those of the reference concrete), respectively. Specifically, W6, W8, and W11 represent 6%, 8%, and 11% water reduction, respectively; and C2 and C5 represent 2% and 5% cement reduction, respectively.

The selected dosage of the admixed UEO was determined based on the optimum effect on the workability of mix R obtained by varying the dosage (in the range of 0.1%–2.0% by weight of cement). Herein, workability was chosen as a determining parameter because it is directly influenced by water, which is also a well-known influencing factor of the mechanical and durability performances of concrete. Mix U-W6 contains 6% less water than mix U, and its w/c is 0.586. The 6% water reduction was chosen based on the 5% minimum requirement in ASTM C494 for a chemical admixture to be a so-called water reducer. Reduced water (*i.e.* 8% and 11% relative to the water content of mix R) and cement (*i.e.* 2% and 5% relative to the cement content of mix R) contents of mixes U-W8C2 and U-W11C5 were found in the trials. Further reduction in the water and cement contents was stopped following a decrement in the workability. The reduction in the water and cement contents of mixes U-W8C2 and U-W11C5 relative to those of mix R was realized by maintaining their w/c values to that of mix U-W6. However, the CP was reduced from mix U-W6 to U-W8C2 to U-W11C5, as mentioned in Table 1. The sequence of the investigation performed in the present study is summarized in Table 2.

Tests on fresh and hardened concrete were performed workability (*i.e.* slump test), air content, setting times, drying shrinkage, compressive and flexural strengths, and F–T durability. These tests are required as per ASTM C494 for the evaluation of chemical admixture of concrete. Details of the methods used for all the tests are presented in the following sections. Unless otherwise stated, the preparation and curing of all the concrete specimens followed ASTM C192 "Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory."

Table 2
Sequence of the investigation.

Stage	Purpose of the investigation	
1	Purpose:	Optimum dosage of the UEO
	Mix:	R (*i.e.* with different dosages of the UEO between 0 and 2% BWOC*)
2	Purpose:	UEO effect on the properties of concrete
	Mix:	U (*i.e.* mix R + optimum dosage of the UEO as determined in stage 1)
3	Purpose:	Chemical admixture type of the UEO in accordance to ASTM C494
	Mix:	U-W6 (*i.e.* mix with the UEO and less water content as per requirement in ASTM C494)
4	Purpose:	Coupling effects from admixing the UEO and reducing the CP (*i.e.* water and cement) on the properties of concrete
	Mix:	U-W6, U-W8C2, and U-W11C5 (*i.e.* mix with the UEO and less CP)

*By weight of cement

2.2. Workability and air content of fresh concrete

The workability and air content of the fresh concrete were determined following the procedures in ASTM C143 "Test Method for Slump of Hydraulic-Cement Concrete" and ASTM C138 "Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete," respectively. The air content (A) was calculated using Equation (1), where T is the theoretical density of the concrete computed on an air-free basis and D is its measured density.

$$A = \left(\frac{T\text{-}D}{T}\right)100 \tag{1}$$

2.3. Mechanical properties of hardened concrete

The setting times, drying shrinkage, and compressive and flexural strengths (after curing of 3, 7, and 28 days under lime saturated conditions) of the concrete specimens were determined by following the procedures in ASTM C403 "Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance," ASTM C157 "Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete," ASTM C39 "Test Method for Compressive Strength of Cylindrical Concrete Specimens," and ASTM C78 "Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)", respectively. The curing process for the drying shrinkage test was performed in accordance with ASTM C494.

2.4. Freezing and thawing durability

Prismatic specimens of concrete were prepared, cured, and exposed to the F–T cycle in water in accordance with procedure A of ASTM C666 "Test Method for Resistance of Concrete to Rapid Freezing and Thawing." The relative mass loss and dynamic modulus of elasticity (P_N) (*i.e.* as compared to their initial values prior to F–T exposure) were determined for each mix specimen after every 36F–T cycles within a total of 300F–T cycles. Each F–T cycle test was terminated when the relative dynamic modulus of elasticity (P_N) of the specimen reached 60% prior to the 300F–T cycles. A non-destructive test implementing an ultrasonic pulse was employed for obtaining P_N [28]. P_N was calculated using Equation (2), where V_0 and V_N are the velocities of the ultrasonic pulse transmitted through the specimen under its initial condition (*i.e.* before the F–T exposure) and after N F–T cycle exposure, respectively. Further, ρ is the surface saturated condition (SSD) density of the specimen, μ is Poisson's ratio of the concrete, and V_0 and V_N (V) are calculated using Equation (3) as per ASTM C597 "Standard Test Method for Pulse Velocity Through Concrete." In addition, L is the length of the specimen and T is the transit time of the ultrasonic pulse transmitted through the concrete. The F–T durability factor (DF) is calculated using Equation (4), where N is number of cycles at which P_N reaches a specified minimum value for discontinuing the test (*i.e.* until P_N reaches 60% of the initial modulus or 300F–T cycles, whichever occurs first). M is the specified number of cycles at the F–T exposure that is to be terminated.

$$P_N = \frac{E_N}{E_0}100 = \frac{V_N^2}{V_0^2}100 \tag{2}$$

$$V = \frac{L}{T} \tag{3}$$

$$DF = \frac{P_N N}{M} \tag{4}$$

3. Result and discussion

3.1. Dosage of admixed UEO

In Fig. 2, the slump of mix R at different dosages of the admixed UEO is presented. Increment in the dosage beyond 0.5% *by weight of cement (BWOC)* does not further increase the slump. This plateau trend in the slump beyond a certain dosage is also reported from a previous study [29]. Based on non-changing slump with the addition of UEO beyond 0.5% (BWOC), this value was chosen as the optimum dosage. Although a higher dosage is considered to aid a higher incorporation of a UEO and can further assist its waste management, in previous studies, it is reported that increasing dosage of an admixed UEO adversely affects the mechanical properties of concrete [29,30]. The presence of oil in contaminated sand is also demonstrated to have an adverse effect on the compressive strength of a mortar formed of sand with oil contamination above 1%–2% [31–33]. A decreased compressive strength of a concrete containing sand with oil contamination of up to 1.5% is also reported [34]. The optimum dosage of 0.5% BWOC of the UEO was admixed into mixes U, U-W6, U-W8C2, and U-W11C5.

3.2. Effect of admixed UEO on properties of concrete

The investigation of the effect of the admixed UEO on the properties of the concrete was performed by comparing the test results of the specimens of mix R and mix U. The results of the various tests performed on the fresh and hardened concretes are summarized in Table 3. The tests on the fresh concrete were for the workability and air content, whereas those on the hardened concretes were for the setting times, drying shrinkage, compressive and flexural strengths, and F–T durability. It is newly found that the admixed UEO affects the drying shrinkage and the F–T durability.

The admixed UEO causes an incremental effect on the slump and air content, in agreement with the result of a previous study [24]. This indicates that the varied source of UEO (*i.e.* synthetic and mineral UEO used in previous studies and semi-synthetic used in present study) can result in the same effect on concrete properties. The initial setting time is delayed in the presence of the

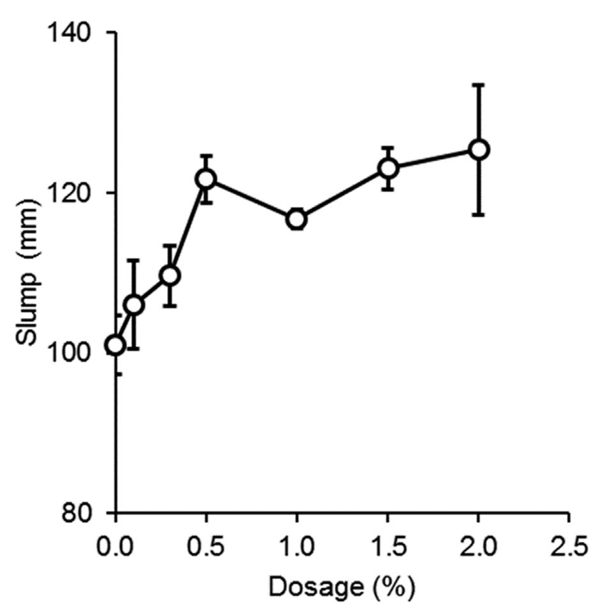

Fig. 2. Effect of the admixed UEO dosage (*i.e.* BWOC) on the slump of mix R measured in accordance to ASTM C143.

Table 3
Effect of the admixed UEO on fresh and hardened concrete properties. "~" indicates that the effect of the admixed UEO is assumed to be within the standard error of the test.

Concrete properties	Mix code		Effect of admixed UEO
	R	U	
Slump (mm)	101 ± 4	122 ± 3	↗
Air content (%)	2.7 ± 0.5	10.1 ± 0.2	↗
Setting time			
Initial (min)	355 ± 9	415 ± 5	↗
Final (min)	603 ± 47	675 ± 36	~
Compressive strength			
3 days (MPa)	16.5 ± 0.4	14.7 ± 0.2	↘
7 days (MPa)	27.4 ± 0.3	24.4 ± 0.7	↘
28 days (MPa)	40.0 ± 1.2	34.1 ± 0.5	↘
Flexural strength			
3 days (MPa)	3.9 ± 0.5	4.1 ± 0.2	~
7 days (MPa)	5.8 ± 0.6	5.5 ± 0.1	~
28 days (MPa)	7.3 ± 0.1	6.8 ± 0.3	↘
Length change (%)	−0.0230 ± 0.0072	−0.0161 ± 0.0008	~
F–T resistance			
DF (%)	785 ± 2	535 ± 66	↗
Mass loss			
After 36F–T cycles (%)	−1.33 ± 1.93	0.14 ± 0.06	n/a
After 72F–T cycles (%)	−43.95 ± 29.96	−19.64 ± 14.55	↘
Visual appearance			
After 72F–T cycles	R U 		↘

admixed UEO. The change in the final setting time due to the admixed UEO is insignificant. As shown in Table 3, there is an overlapped range between the upper range and lower range of final setting time of mix R and mix U, which is 650 and 639 min, respectively. The differences in the effects of the admixed UEO on the final setting times obtained from the present and previous studies can be ascribed to the minor substance and its concentration (*i.e.* affecting cement hydration) in the UEO. This substance can vary depending on the source of the UEO. In a previous study, the earlier final setting time of concrete with a UEO is attributed to the presence of chloride and nitrite in the UEO [20]. The mechanical properties of concrete with the admixed UEO, in terms of the compressive and flexural strengths, are decreased, probably by the increased air content.

The lower length change due to drying in mix U as compared with that in mix R suggests that the mix with the UEO experiences lower drying shrinkage, which can be related to the lower CP in mix U (owing to its higher air content). Drying shrinkage is caused by the evaporation of water from the capillary pores of hydrated cement. The F–T resistance of the concrete is increased by the UEO, as indicated by the higher DF and lower mass loss from mix U than those from mix R. The DF was calculated after 36F–T cycles. After the 36 cycles, the relative dynamic modulus of elasticity (P_N), as calculated using Equation (2), is less than 60%. The mix R specimen loses its mass after 36F–T cycles, whereas the mix U specimen gains mass, even with the loosened concrete surface. The increasing mass of the mix U specimen can be due to the gradual intrusion of water (that was used to immerse the specimen in the F–T chamber) into the air pocket, the mass of which is more dominant than that of the loosening concrete. The mass loss of the mix U specimen is distinctively less than that of the mix R specimen after being subjected to 72F–T cycles. After the 72F–T cycle exposure, the mix U specimen is visually more intact than the mix R specimen. The mix R specimen is divided roughly into two halves that exhibited its initial condition, whereas the mix U specimen iss only damaged at its rumbling surface. Overall, the mass losses, DF, and visual observations of the specimens of mixes R and U indicates that the concrete with the UEO is more resistant to the F–T cycles. An entrained air void can act as an empty chamber to relieve water through volumetric expansion during freezing, causing the exerted pressure on the concrete to be reduced [35,36].

The effect of the admixed UEO (based on Table 3) confirms the existing reports regarding the ability of a UEO to serve as a water reducer and an air entraining agent. The newly found feature of the studied UEO is drying shrinkage reduction. The advantageous effects of admixing the UEO on the concrete properties are increased workability, less internally induced stress (caused by drying shrinkage), and more durability to the weather cycle in a region experiencing four seasons. The concrete properties that need to be noted when admixing a UEO are the initial setting time

Table 4
Effect of the admixed UEO on the concrete properties relative to the requirements of a type A water reducing admixture in ASTM C494.

Concrete property	Mix U-W6	Type A water reducing admixture		
		Limit		Fulfillment of mix U-W6
		Lower	Upper	
Water content (%)	94	n/a	95	Yes
Time of setting				
Initial (min)	379	295	445	Yes
Final (min)	629	543	693	Yes
Compressive strength				
3 days (%)	111	110	n/a	Yes
7 days (%)	106	110	n/a	No
28 days (%)	101	110	n/a	No
Flexural strength				
3 days (%)	122	100	n/a	Yes
7 days (%)	98	100	n/a	No
28 days (%)	101	100	n/a	Yes
Length change				
First criteria (%)	70	n/a	135	Yes
Second criteria (%)	−0.007	n/a	+0.010	Yes
Relative DF (%)	535	80	n/a	Yes

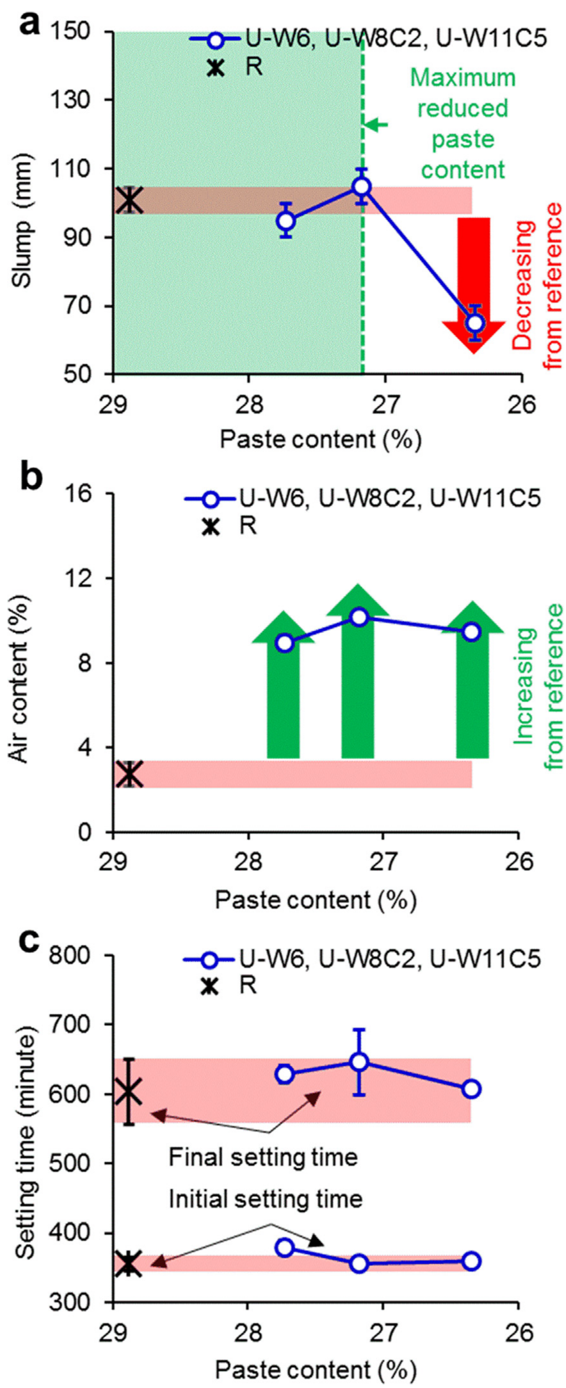

Fig. 3. Measured properties of the fresh concrete: (a) slumps and (b) air contents of mixes U-W6, U-W8C2 and U-W11C5 as compared to those of mix R. (c) Initial and final setting times of mixes U-W6, U-W8C2, and U-W11C5 as compared to those of mix R. The contents of the cement paste (CP) of mixes R, U-W6, U-W8C2, and U-W11C5 are 28.9%, 27.7%, 27.2%, and 26.3%, respectively. w/c is 0.623 for mix R and 0.586 for mixes U-W6, U-W8C2, and U-W11C5.

and the reduced compressive and flexural strengths. A shifted initial setting time can be an advantage or a disadvantage of admixing a UEO depending on the expected timeframe for setting the concrete. However, the decrease in the mechanical properties (particularly compressive strength) of the concrete due to the admixed UEO is a drawback that needs to be addressed. In a composite material, concrete is only considered to bear the compressive stress, and other types of stress are endured by the reinforcing material, such as steel and fiber-reinforced polymer (FRP) [37].

The effects of admixed UEO on slump, strengths, length change due to drying shrinkage and F-T durability can be explained as the effect of increased air content in the concrete with UEO. The slump is increased by the generation of air bubbles from the use of air-entraining agent [38]. The reduced strengths are due to the air void from the entrained air caused by the admixed UEO. The decreased length change due to drying shrinkage can be attributed to the less evaporable water due to more air content in concrete with admixed UEO. The increased F-T durability can be explained by the mechanism that the presence of entrained air provides a pressure (*i.e.* due the expanding volume of water during freezing) release [39].

3.3. Chemical admixture type of UEO

Based on the improvement in the workability of mix R on admixing the UEO (*i.e.* mix U), as can be seen from Table 3, evaluation was initiated in accordance with the specifications of a type A water reducing admixture provided in ASTM C494. A type A water reducing admixture requires minimum 5% water reduction relative to that of the reference concrete while retaining the properties of the fresh and hardened concrete satisfactorily to satisfy the requirements in ASTM C494. In order to investigate the compliance of UEO to a type A water reducing admixture, the relative changes in properties of mix U-W6 (*i.e.* with 6% water reduction) from those of mix R were matched with the requirement of ASTM C494. Table 4 shows the relative change in properties of mix U-W6 from those of mix R and their compliance to the requirement in ASTM C494.

The effect of the admixed UEO on the concrete properties suggests that the UEO mostly complies with the requirements of a type A water reducing admixture as specified in ASTM C494, except those for the 7 and 28 days compressive and flexural strengths. The 7 and 28 days compressive strengths of mix U-W6 are higher than those of mix R but the increased strengths does not meet the requirement of a type A water reducing admixture. The 7 days flexural strength is 2% lower than that of mix R. However, the 28 days flexural strength is 1% higher than that of mix R and meet the requirement of a type A water reducing admixture. According to ASTM C494, the use of a type A water reducing admixture should result in equal flexural strength up to the concrete age of 28 days. Considering the significant increase in the air content and DF, the use of an anti-foaming agent can be considered to lower the former to further enhance the strength while still fulfilling the required DF and other properties. For example, commercially available oil-based and silicone-based anti-foaming agents have been demonstrated to effectively control the excessive increment in the air content of concretes containing UEOs [20]. Therefore, it is suggested that a UEO-based type A water reducing admixture can be formed by incorporating an anti-foaming agent into the UEO.

3.4. Coupling effects of admixing UEO and less content of cement paste

In this section, the investigation on the changes in the properties of concrete with UEO (*i.e.* after implementing its water reducing feature) along with CP reduction is elaborated. The investigation was performed by comparing the test results of the specimens of mix R and mixes U-W6, U-W8C2, and U-W11C5. It is to be recalled that these mixes have lower w/c than mix R. Therefore, the comparison of the properties of mix R and mixes U-W6, U-W8C2, and U-W11C5 also indicates the capability of employing the water reducing feature of the UEO to minimize the cement content. The CP decreases from mix U-W6, U-W8C2, to U-W11C5, as can be seen from Table 1. The slumps, air contents, and setting times of mixes U-W6, U-W8C2, and U-W11C5 are dis-

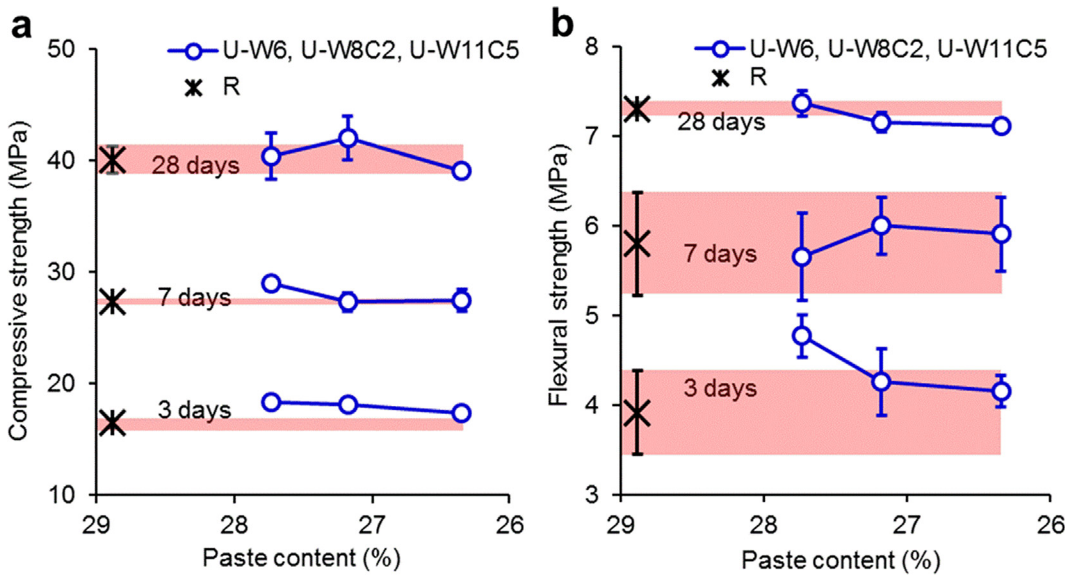

Fig. 4. (a) compressive and (b) flexural strengths of the concrete after 3, 7, and 28 days of curing ages of mixes U-W6, U-W8C2, and U-W11C5 as compared to those of mix R.

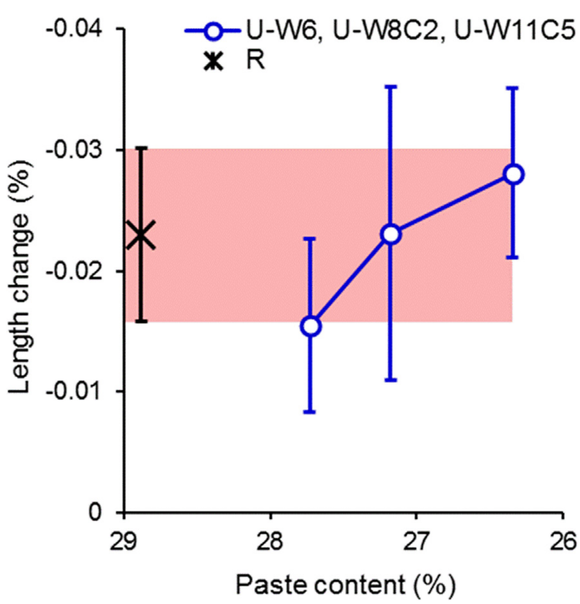

Fig. 5. Length changes (*i.e.* due to the drying shrinkage) of the specimens of mixes U-W6, U-W8C2, and U-W11C5 compared to that of mix R.

played in Fig. 3. Fig. 3a shows that the CP reduction to 27.2% results in a comparable slump to that of mix R. Additional reduction in the CP to 26.3% significantly decreases the slump and is apparently a limiting factor in further lowering the CP. From Fig. 3b, the increasing effect of the admixed UEO on the air content can be observed. Fig. 3c exhibits that the initial and final setting times of the mixes with a CP reduction to 26.3% are comparable to those of mix R.

Fig. 4 shows the effect of the CP reduction on the compressive and flexural strengths of the concrete with the UEO. The strengths of mix R at the ages of 3, 7, and 28 days are comparable to those of mixes U-W6, U-W8C2, and U-W11C5, which indicate the capability of employing the water reducing feature of the UEO to counter its adverse effect on the strengths. The tendency of the decrease in the strengths with increasing CP can be owing to the increase in the interfacial transition zone (ITZ), which surrounds the aggregates. An ITZ has a weaker structure compared to the bulk hydrated cement and is more fragile to mechanical loads. The CP reduction consequently increases the volumetric content of the aggregate as well as its surrounding ITZ (*i.e.* as a part of aggregate-CP interface). The previous studies shows that the thickness of ITZ (*i.e.* as observed from SEM) is influenced by the size and type of aggregates and w/c [40,41]. Therefore, it is expected that the ITZ thickness remains to be the same due to the use of the same type and proportion (*i.e.* fine to coarse aggregate ratio) of aggregates. The w/c of mix U-W6, U-W8C2, and U-W11C5 are also the same.

Fig. 5 presents the effect of the CP reduction on the length change (due to the drying shrinkage) of concrete containing the UEO. Reduced length changes (*i.e.* as compared to the length change of mix R) due to the CP reductions are obtained for the mixes with CP of 27.7% and 27.2%. These reduced length changes can be owing to the effect of the lower w/c and CP than those of mix U, resulting in less evaporation of water during drying. However, CP reduction alone from mix U-W6 to U-W11C5 (*i.e.* from CP of 27.7% to 26.3%) tends to increase the length change, which can be caused by the increasing volumetric content of ITZ in concrete (*i.e.* accompany the increased aggregate content and less CP). It is understood that the length change due to a drying shrinkage in concrete is CP related phenomena [42]. The length change is caused by the drying process of water from the pores of CP. The presence of aggregates in concrete provides a restraining effect towards the length change [43]. The existing experimental result shows that a larger pore (*i.e.* within the ITZ) will be easier to dry than a smaller pore (*i.e.* in the bulk hydrated cement) [44]. The relatively larger pores within the ITZ are caused by the less packing density of cement particles at the aggregate-CP interface due to the so-called "wall effect" [45]. It is also indicated that the increment in restraining effect of aggregates towards the length change decreases with an increasing content of aggregates [46]. These existing experimental results indicate that the length change is not only affected by the CP but also the relatively larger size of pores at ITZ. Therefore, the tendency in increasing the length change from mix U-W6 to U-W11C5 (*i.e.* from CP of 27.7% to 26.3%) can be caused by a more dominant effect from increasing

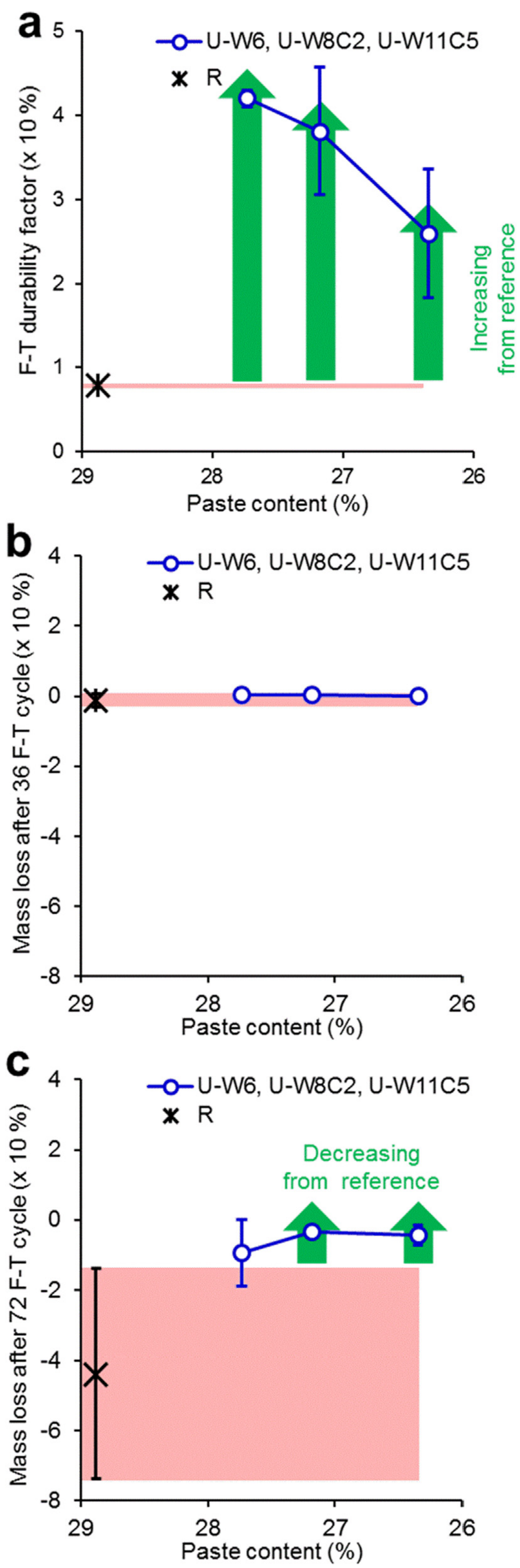

Fig. 6. (a) F–T durability factors (after 36F–T cycles) and (b) mass losses of mixes U-W6, U-W8C2, and U-W11C5 after 36 and 72F–T cycles compared to those of mix R.

the volumetric content of the ITZ (*i.e.* contains relatively larger pores) than the effects of reducing the CP.

The DF and mass losses of the specimens after F–T cycles are displayed in Fig. 6. It can clearly be seen that higher resistances to the exposure to the F–T cycles can be achieved for mixes U-W6, U-W8C2, and U-W11C5 as compared to that of mix R. The decreasing tendency of the DF with the CP reduction can be owing to the increasing ITZ, which is more vulnerable to the F–T cycle exposure. Fig. 7 presents the specimen conditions after the F–T cycles.

The criteria of coupling effect from admixing UEO and CP reduction is the comparable or better workability, air content, setting time, strengths, length change due to drying shrinkage and F-T durability (*i.e.* as compared to those of reference concrete). It is found that the CP reduction from 28.9% to 27.2% results in comparable workability, setting time, strengths and length change due to drying shrinkage and improved air content and F-T durability. The mechanism of coupling effect from admixing UEO and CP comes from water reducing feature of admixed UEO that allows the concrete mix with lower w/c along with reduced CP from 28.9% to 27.2%. It is found that further CP reduction (*i.e.* down to 26.3%) is limited by a significant reduction in workability. Theoretically, the workability (*i.e.* slump) is controlled by water content of concrete. CP reduction simultaneously lowers the water content and workability [47]. The lower w/c decreases the setting time of concrete (*i.e.* delayed by the UEO) and compensates the adverse effect of UEO on strengths. Setting time shortens and strengths increase with lower w/c [48 49]. The comparable length change due to drying shrinkage can be attained due to the opposite effect between UEO, w/c and CP reduction (*i.e.* decreasing effect) and higher volumetric content of ITZ (*i.e.* increasing effect). The volumetric content of ITZ increases due to the higher aggregate content of concrete with lower CP. The effect from UEO, w/c and CP reduction can be seen from the reduced length change of mix U-W6 that the CP reduction is down to 27.7%. The effect of higher volumetric content of ITZ can be seen from the tendency in increasing length changes from mix U-W6 to mixes U-W8C2 and U-W11C5 (*i.e.* with CP of 27.2%, and 26.3%, respectively). Nevertheless, the resulted length changes of mixes U-W6 to U-W8C2 and U-W11C5 are still comparable to that of mix R. The improved F-T durability is resulted from the air entraining feature of UEO.

Comparison of the properties of the specimens of mix R and those mixes with CP reduction (*i.e.* mixes U-W6, U-W8C2, and U-W11C5) demonstrates the suitability of using the UEO as a chemical admixture to minimize the cement content in the concrete. The CP reduction from 28.9% (mix R) to 27.2% (mix U-W8C2) corresponding to a 2.0% cement reduction results in satisfactory properties of concrete with respect to those of mix R as the reference. It should be noted that the 2.0% cement reduction is the value calculated based on the designed composition. On considering the difference in the air contents of mix R and U-W8C2, the reductions in the water, cement, and aggregates in mix U-W8C2 relative to those in mix R are 14.9%, 9.4%, and 5.4%, respectively.

4. Conclusion

In this study, various tests related to the use of a UEO as an alternative chemical admixture for a normal strength concrete were performed. The investigation was focused on the effect of the admixed UEO on the concrete properties, chemical admixture type of the UEO as per ASTM C494, and coupling effects of admixing the UEO and reducing the content of the cement paste (CP) on the concrete properties. The results demonstrate the following:

1. The UEO is confirmed to possess the characteristics of a water reducer and an air entraining agent. The increased air content can explain the other effects on concrete properties (*i.e.* except setting time) from admixing UEO. The admixed UEO is found to delay the initial setting time while not affecting the final setting time. The differences in the effects on the final setting time

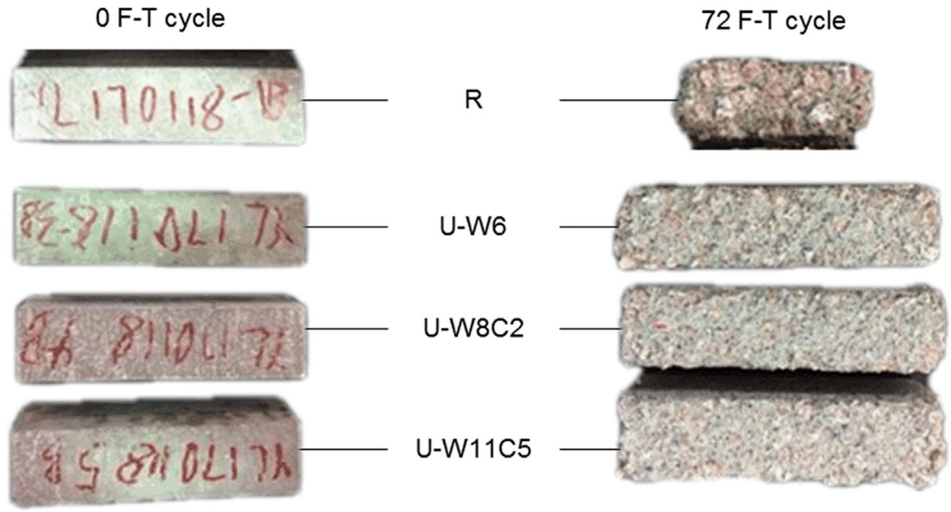

Fig. 7. Comparison on the specimen conditions of mixes R, U-W6, U-W8C2, and U-W11C5 in the initial stage and after 72F–T cycles. After the 72F-T cycles, it is noticeable that the specimen of mix R is lost more significantly than the specimens of mixes U-W6, U-W8C2, and U-W11C5.

obtained from the present and previous studies can be owing to the variation in the minor substance in the different sources of the UEO. The newly found feature of the UEO is its ability to serve as a drying-shrinkage reducing agent. Furthermore, the previously reported improved freezing and thawing resistance of concrete with a UEO admixture is confirmed in this study.

2. The UEO mostly complies with the specifications of an ASTM C494 type A water reducing admixture. However, the increase in the strengths of the concrete is lacking compared to the required effect in accordance with ASTM C494 for using a type A water reducing admixture.
3. The water reducing and air entraining features of the UEO enable a concrete mix with a low w/c and CP content (*i.e.* up to 9.4% reduction in the cement content) but with comparable properties to those of the reference concrete. This information provides a basis for a relatively more economical and ecological production of concrete by admixing a UEO and reducing the cement content than currently.

The information from the present study presents useful guidance for the field applications of a UEO as a chemical admixture. As an example, UEOs can be perceived as highly economical and ecological chemical admixtures that can be alternatives of type A water reducing admixtures. The use of the water reducing feature of a UEO as a chemical admixture can be combined with CP reduction to minimize the cement content. To further validate the utilization of the considered UEO as a chemical admixture in field applications, the future study can include:

1. Investigation of the long-term effects of the admixed UEO on the concrete properties. This will complement the information from the present study to provide a more comprehensive knowledge for the effect of admixed UEO on the time-dependent properties of concrete.
2. Obtaining a more detailed effect of the constituents of the UEO on the concrete properties and of the characterization techniques of UEOs, which can be useful for quality control and quality assurance. The focus of future study can be put on the constituent that affect the air content and setting time.

CRediT authorship contribution statement

Yohannes L. Yaphary: Conceptualization, Methodology, Writing - original draft. **Raymond H.W. Lam:** Conceptualization, Methodology, Supervision. **Denvid Lau:** Conceptualization, Methodology, Writing - review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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