Mechanical Behavior of Corroded Steel in Lightweight Concrete: A Review

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Abstract. There is an immediate need for reinforced concrete (RC) construction to protect natural resources and environmental sustainability due to a gradual decline in natural resources and a problem in many waste disposal sites used. Reducing natural stones as aggregates in concrete using agriculture waste as aggregate to produce lightweight concrete is an effective way to reduce this problem. Lightweight concrete applications for structural design have long been applied because they significantly benefit design and construction costs. However, limited information about the structural performance, such as the bond strength, the compressive strength can be a barrier to applying lightweight concrete in the construction industry, as inadequate bond strength can result in structural deficiencies in RC structures. Therefore, to launch the use of lightweight concrete as a general material of construction, this research was conducted to review the current information on the mechanical behaviour of corroded lightweight concrete structures, while agricultural solid wastes were used as a lightweight aggregate in the concrete mixture.

1. Introduction

Palm oil is one of the industrial commodities growing rapidly today, especially in tropical countries such as Indonesia, Malaysia, and Nigeria. According to the Ministry of Agriculture of the Republic of Indonesia, there are 9.1 million hectares of palm oil plantations with 30-40 million tonnes of oil palm from 2013 to 2015 in Indonesia [1, 2]. However, one significant problem of the palm oil industry is that it produces many palm oil solid wastes. For 1 tonne of palm oil, it will produce oil palm waste in the form of oil palm empty bunches as much as 23% or 230 kg, shell waste as much as 6.5% or 65 kg, wet decanter solid (palm sludge) 4% or 40 kg, fiber 13% or 130 kg and oil palm mineral waste as much as 50% [3].

The use of the agricultural solid wastes such as oil palm shell (OPS) as a material in lightweight concrete (LWC) structures must guarantee the bonding between the cement matrix and the aggregate and bonding between the reinforcement and the surrounding concrete to withstand external loads effectively [4,5]. Today, LWC is still considered less durable than normal concrete due to its more porous existence regardless of aggregate types and concrete composition [6]. LWC is usually used in the light, thermal, fire-resistant, low shrinkage constructions, and cracking resistance in normal conditions [5,7]. Various variables, including form and grading aggregation, water content, cement content, w/b ratio, and curing conditions, affect the structural performance of LWCs. Low-density (400 to 800 kg/m³), medium (800-1350 kg/m³) and high (1350-1850 kg/m³) are typically classifiable by density for LWCs. The LWC can be categorized into three groups: low-density LWC for non-structural applications, medium-density LWC depending on field requirements, non-structural and structural applications, and high-density LWC may be used as structural applications [8].
A comparative study by Mo et al. [4] regarding the bond strength revealed that OPS lightweight concrete's bond strength is about 50-80% higher than normal concrete. Other studies [4,9-12] have also focused mainly on OPS lightweight concrete's bond strength with normal steel reinforcement that does not have rust (i.e., no corrosion). Even though the steel reinforcement of concrete structure could experience corrosion due to one of the concrete mixture components, i.e., remaining water and the surrounding environment’s influence, such as concrete buildings on the coastal area, the steel corrosion could reduce the bond strength of the concrete structure. In addition, steel corrosion could reduce the concrete structure's service life, especially for the LWC structures. Therefore, this research addresses the most important developments in the mechanical behavior of the LWC structures subject to deterioration of concrete; corrosion of steel reinforcement. This review aims to encourage a better understanding of the mechanical behavior of non-corroded and corroded steel in LWC and to emphasize certain potential research requirements in this area.

2. OPS Lightweight Concrete
Concrete can become LWC with one of its components. The most suitable method is to use lightweight aggregates instead of normal weight aggregates in the concrete mixture, while the concrete quality maintains the same. Replacements of the concrete materials are done to save natural resources, utilize waste, and most importantly, make construction costs cheaper [13]. LWC is currently in dire need to preserve natural resources due to the gradual decrease in natural resources such as cement and aggregate (i.e., sand and stone) that are often used as concrete materials. And also, to preserve the environment due to problems with a large amount of waste disposed of in limited landfill space, such as waste from pulverized coal and agricultural waste. One of the most common ways to reduce this problem is by reducing natural stone as aggregate in the concrete instead of using agricultural waste and recycled material as a substitute (partially and fully) of the aggregate in the concrete structure. At this time, agricultural waste, which is often used as a mixture and substitute for aggregate in the concrete structure, is palm oil waste (shell), coconut waste (shell), corn waste, and rice waste (husk) [14-20] and also the recycled material such as recycled aggregate concrete (RAC) [5, 7, 21-23]. Oil palm shell (OPS) waste is the hardest component of oil palm, which has not been used optimally. The OPS can be used as activated charcoal, liquid smoke, fuel, and concrete material [3, 14]. The OPS lightweight concrete has been carried out since 1984 by Abdullah [24] in Malaysia and Okafor [25] in Nigeria. OPS lightweight concrete that uses OPS as a substitute for aggregate is defined as lightweight concrete.

![Figure 1. Oil Palm Shell (OPS) [4]](image-url)
3. Mechanical Behaviour of OPS Lightweight Concrete

3.1. Compressive Strength

In practice, compression strength is the most common parameter used to describe the LWC quality [26]. The OPS lightweight concrete has been successfully developed in the past, and it is generally only suitable for compressive strength of 20 MPa to 35 MPa with a density of about 20–25% lower than normal weight [27-29]. No detailed research reports on how to increase the strength of lightweight concrete using this agricultural solid waste. Basri et al. [28] stated that OPS lightweight concrete is around 50% less compressive than normal concrete. Mannan and Ganapathy [29] suggest that OPS lightweight's compressive strength is between 20 and 24 MPa. Okafor [25] maintains that OPS can not produce lightweight concrete with a compressive strength of more than 30 MPa. However, the 28-day compressive strength of more than 30 MPa can be obtained for OPS concrete with improved quality of OPS consistency. The studies by Alengaram et al. [30] and Shafigh et al. [16] showed that OPS could produce lightweight concrete with 28-day compressive high strength, i.e., 36 MPa and 40 MPa, respectively. Alengaram et al. [30] use fly ash and silica fume, 1.6 of a sand/cement ratio, and 0.35 of water/binder ratio to achieve the highest 28-day compressive strength. To demonstrate OPS's potential use as aggregates in lightweight concrete, two small structures have been constructed at University Malaysia Sabah (UMS) that are located near the coastal area. This structure consists of a small bridge with about 2 m and a low-cost house with a floor area of about 59 m² [31].

3.2. Flexural Strength

Flexural strength is a mechanical framework for brittle materials and is defined as a material’s capability to combat distortion under load [32]. Alengaram et al. [33] showed that OPS lightweight concrete could produce double the flexural strength when compared with normal-weight concrete. The OPS lightweight concrete was found to have a 28-days flexural strength of the prism specimens of 2.54 MPa – 5 MPa by adding the fly ash and Palm Oil Fuel Ash (POFA) as a partial substitute of cement, respectively [1, 34]. Before the flexural strength test, the LWC containing POFA was put under various curing regimes: air, spray, water, and natural environment curing. Water curing is also the best curing OPS lightweight concrete method due to increased hydration and pozzolanic reactions, leading to a higher volume of C-S - H gel. It increases OPS lightweight concrete's flexural strength as the gel fills the existing concrete voids, rendering it denser and heavier [34].

Yew et al. [35] and Yap et al. [36] deduced that the addition of poly-propylene fibers (non-metallic fibers) and steel fibers had been shown to increase the flexural strength of OPS lightweight concrete by up to 0.25% and 1%, respectively. In order to increase the flexural strength of OPS lightweight concrete, the effect of adding poly-propylene fibers at low volume fractions (up to 0.25%) is more pronounced. [35]. The addition of steel fiber up to 3% by volume improved OPS lightweight's mechanical properties, i.e., flexural strengths of 18.5 MPa [36]. Shafigh et al. [37] concluded that steel fiber's addition raises the flexural strength levels by up to 17%. The findings have shown that the 28-days flexural strength rises from 5.42 MPa to 7.09 MPa as fibers rise from 0% to 1%. Steel fiber can reduce OPS lightweight concrete's sensitivity in poor curing conditions as an alternative material [37]. In addition, Shafigh et al. [38] showed that crushed OPS of LWC has a flexural strength range of 4.4 – 7.0 MPa. Alengaram et al. [39] concerning mechanical properties, OPS lightweight concrete, have more warning than normal-weight concrete before failure. In addition, compared with the brittle failure of normal-weight concrete beams, the mode of failure found in OPS lightweight concrete was ductile.

3.3. Bond Strength

Bond strength is an important structural feature and influences concrete structures [40]. Insufficient bond strength may lead to a loss of tensile compatibility on concrete structures and lead to excess slippage, leading to irreversible deformation of concrete structures. Two forms of action transfer bond strength, namely adhesion and mechanical friction, enabled by various pressure states on the concrete structures. This behavior will primarily rely on the surface texture and geometry of the steel reinforcement of the concrete structure [41]. The adhesion refers to the bond between the steel reinforcement and the concrete and the frictional from the concrete and steel reinforcement's roughness.
The bond strength between concrete and steel reinforcement is also influenced by concrete structures, as different types of concrete structures have different concrete mixtures. In self-compacting concrete (SCC), for example, the researchers [43-45] reported the higher bond strength between concrete and steel reinforcement than normal concrete, which was associated with a low water ratio. Similarly, for concrete structures using recycled aggregates, the bond strength was higher than normal concrete [40, 46], and this was due to internal curing actions on recycled aggregates [40]. On the other hand, concrete and steel reinforcement's bond behavior is commonly studied in OPS lightweight concrete. This type of concrete with the aggregate and the mixed design used on this LWC is also very different from normal-weight concrete. Based on the results of the review conducted by Mo et al. [10], there are conclusions regarding the bond strength between concrete and the steel reinforcement of LWC in general: increased mortar characteristics to increase bond strength compared to normal concrete resulted in lower water ratio of LWC, immersion with water and the addition of steel fibers to LWC usually increase the bond strength, LWC bonding with deformed bars is greater than other forms of steel reinforcement, and the impact of steel reinforcement diameter and bond length on the LWC is very significant. Because the steel reinforcement diameter is smaller and the bond length is shorter, it often increases the bond strength.

Another study conducted by Mo et al. [4] on bond strength on OPS lightweight concrete revealed that the concrete's bond strength is 50-80% higher than normal-weight concrete at the same compressive strength. The higher bond strength in OPS lightweight concrete may be due to the higher quality of cement content used and the interconnected effect between aggregates of OPS lightweight concrete [4, 33]. Several other studies [4, 9, 47, 48] are also related to bond strength on OPS lightweight concrete. However, the studies are limited to testing the bond strength between concrete and steel reinforcement, where specimen type and compressive strength remain the same. Also, since there is limited research on the effects of concrete cracking on its bond strength, the nature of bond strength on OPS lightweight concrete is incomplete.

4. Mechanical Behaviour of Corroded LWC
There is a lot of research on the mechanical behaviour of normal-weight concrete structures and lightweight concrete structures that are not corroded. However, research on the mechanical behaviour of the corroded OPS lightweight concrete is very limited. The information about the bond strength and other concrete conditions with various corrosion levels in OPS lightweight concrete structures is very important because it will affect OPS lightweight concrete's serviceability and durabilities, such as crack deflection and service life.

4.1. Compressive Strength
Previous studies have shown that higher risks of steel corrosion of LWC are associated with recycled aggregate concrete (RAC) [22, 23, 50, 51]. The more recycling aggregate mixture increases, the lower the compressive strength value due to RAC's poorer durability properties. Four RAC mixtures with different replacement percentages of recycled coarse aggregates were investigated by Zhao et al. [51]. The results show that high compressive strength values are found in 0% recycled aggregate concrete. Arredondo-Rea et al. [22] made ten RAC mixtures with different percentages of replacement RA. The results showed that the use of 30% or lower amounts of RCA does not significantly influence on compressive strength. After 30% mixture of RCA, the compressive strength decreases significantly.

Steel reinforcement corrosion is started more rapidly in RAC than in normal-weight (conventional) concrete. As the porosity increases and the electrical resistivity decreases, the more RAC contains, the faster corrosion in the steel reinforcement begins. Gurdian et al. [50] and Landa-Sanchez et al. [23] evaluates the behavior of LWC with a decreased environmental effect by substituting recycled aggregate for 100 % of natural coarse aggregate. The RCA was tested for mechanical strength and against reinforcement corrosion under carbonation attack and chloride-contaminated conditions. The use of total natural coarse aggregate replacement by recycled aggregate reduced up to 50% of the compressive strength of the LWC [50]. Since the LWC has reduced mechanical properties, a less dense concrete matrix, and high permeability, green RAC concrete has improved corrosion behaviour, making it a promising approach to higher conventional pollutant aggregates [23]. A comparison of research results
can be seen in Figure 2. It can be concluded that a significant decrease in compressive strength occurs in lightweight concrete with an increase of RAC.

Figure 2. Comparison of compressive strength and % RCA in LWC

4.2. Bond Strength

Zhao et al. [52] showed the results in reinforced concrete samples with stirrups. Although the value of the bond strength of normal concrete was higher than that of RAC, the difference was 15%, not as significant as the reinforced concrete sample with a difference of 30%. According to Fernandez et al. [53] in the research results, there is a higher maximum slip, namely at the RAC, and the slip increases when the additional aggregate recycle percentage is used. According to Berrocal et al. [54], the value of bond strength in normal concrete decreases rapidly, and most of its values decrease to zero at a 2 mm slip. Whereas in FRC (Fiber Reinforced Concrete), lightweight concrete can withstand a decrease in bond strength of about 30% at 5 mm slip through variations in rusting level. The comparison of research results [52-54] can be seen in Figure 3. It can be concluded that an increase in the value of bond strength can lead to an increase in slip value up to the maximum slip value, but there is no decrease in the value of bond strength in the RAC mixed concrete. It proves that lightweight concrete with a mixture of RAC can withstand maximum slip without reducing the concrete's adhesive strength. However, RAC does not produce high quality.

Figure 4 shows the comparison of the research [52][53] about ultimate bond strength and corrosion percentage in lightweight concrete with corroded steel reinforcement. According to Zhao et al. [52] on the results of research on concrete samples with a composition of 50% RAC showed that cracks during the induction of steel corrosion on the concrete surface reduced the confinement of reinforcing steel in the concrete, leading to a decrease in the value of bond strength. According to Fernandez et al. [53], the RAC sample study results showed that the ultimate bond strength value decreased when the corrosion level increased. It can be concluded that as steel reinforcement corrosion increases, the ultimate bond strength value will decrease. It happens due to corrosion can reduce the bonding strength between the concrete and reinforcement. The higher corrosion of steel reinforcement will lose its bonding strength, eventually destroying the concrete.

Figure 3. Comparison of bond strength with slip in lightweight concrete with corroded reinforcement

Figure 4. Comparison of ultimate bond strength and corrosion percentage in lightweight concrete with corroded reinforcement
5. Conclusions
Although there have been several researches and reports regarding the mechanical behaviour of oil palm shell (OPS) lightweight concrete, however, there is still hesitation among civil engineers to consider it as a structural material in their design and apply it in practice especially in corrosive environment due to there is a limited study of corroded OPS lightweight concrete. The information about the mechanical behaviour such as bond strength with various corrosion levels in OPS lightweight concrete structures is very important because it will affect OPS lightweight concrete's serviceability and durabilities, such as cracks deflection and service life. There are still serious issues about this corroded OPS lightweight concrete, which should be further investigated, such as its low modulus of elasticity, behaviour in fire, creep, and time-dependent deformation properties.

6. References
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