An Overview of Characterisation, Utilisation, and Leachate Analysis of Clinical Waste Incineration Ash

Ezliana Ghazali1 · Megat Azmi Megat Johari1 · Mohd Azrizal Fauzi2 · Noorsuhada Md Nor2

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Abstract
As industrial globalisation and waste output continue to grow, solid waste management is one of the most pressing worldwide environmental challenges. Solid wastes include both the heterogeneous mass of urban throwaways and the homogeneous accumulations of agricultural, industrial, and mineral wastes. Clinical waste (CW) has a significant negative influence on both human health and the environment. To dispose hazardous CW, a proper waste management system should be necessary, and incineration should be the best possible option for reducing the volume of this hazardous waste. Incineration is being developed in Malaysia as a means of disposing clinical and hazardous waste. Currently, 170 common CW treatment facilities with 140 incinerators are accessible around the country. The combustion procedure kills pathogens and reduces waste volume and weight, but it leaves a solid residue known as clinical waste ash (CWA), which raises heavy metal, inorganic salt, and organic compound levels in the environment. Because metals are not eliminated during incineration, dumping CWA in a landfill could contaminate groundwater. Leachate is the liquid created when waste decomposes in a landfill and water filters through it. The most common method of disposing of CW ashes is to transfer them to a landfill. Landfills should install a top cover after closure for hazardous waste landfills. Due to a lack of space and the high expense of land disposal, recycling technologies and the reuse of ash in various systems have developed. Clinical waste incineration fly ash (CWIFA), a solid waste substance from CW incineration, typically includes mobile heavy metals and can cause significant pollution when reused. The standard requirement for removing CWIFA in dumpsites should be below the metal limit stated by the U.S. Environmental Protection Agency (USEPA). Much recent research on the usage of CWIFA has concentrated on mitigating their effects on the environment. Several studies have confirmed the utilisation of CWIFA in the construction field and agriculture to reduce the leaching of its hazardous components into the environment. Compressive strength decreased with the percentage amount of CWIFA due to the substitution of cement with CWIFA. CWIFA mix with 20% cement is the broad-scale application of CWIFA for geotechnical constructions. Heavy metals (Cd, Cu, Ni, Pb, and Zn) are strongly immobilised by the cementitious matrix. Solidification/stabilisation (S/S) materials can be dumped in landfills with less environmental protection than untreated waste. When utilising a CWIFA in mortar, the primary environmental concern is if any harmful materials leach out during the initial curing process or throughout the life of the mortar. Toxicity characteristic of leaching procedure (TCLP) analysis of all CWIFA specimens found amounts of heavy metals below regulatory limits. Solidification of waste with cement and solidified waste has become a popular way of minimising the atmosphere’s emissions. The amount of CWIFA generated is expected to increase nationally and globally. There is an immediate need for further evaluation of ash leachate investigations for proper disposal and usage of ash in construction materials.

* Ezliana Ghazali
ezliana_maf@yahoo.com

Megat Azmi Megat Johari
cemamj@usm.my

Mohd Azrizal Fauzi
azrizal@uitm.edu.my

Noorsuhada Md Nor
ida_nsn@uitm.edu.my

1 School of Civil Engineering, Universiti Sains Malaysia, Engineering Campus, Nibong Tebal, Pulau Pinang, Malaysia
2 Centre for Civil Engineering Studies, Universiti Teknologi MARA, Cawangan Pulau Pinang, 13500 Permatang Pauh, Pulau Pinang, Malaysia
Highlights

• Clinical waste (CW); Clinical waste Ash; Concrete; Leachate; Environmental; Clinical waste incineration fly ash (CWIFA); Clinical waste incineration bottom ash (CWIBA); Municipal waste fly ash (MWFA)

Keywords Clinical waste ash · Concrete · Leachate · Environmental

Abbreviations

CW Clinical waste
CWA Clinical waste ash
CWIFA Clinical waste incineration fly ash
CWIBA Clinical waste incineration bottom ash
MSW Municipal solid waste
MWFA Municipal waste fly ash

Introduction

There is a lot of clinical waste (CW) in the present pandemic, which resulted in a considerable rise in the quantity of challenging medical waste worldwide (Asian Development Bank (ADB) 2020), therefore, increasing the CWA produced from the incinerator. The increasing CWA will be challenging and problematic to dispose of in controlled and uncontrolled landfills. Incineration is not a final disposal technique because it produces ash that must be disposed of or buried. The incineration process, however, transforms the waste into non-toxic, non-hazardous, and non-putrescible and minimizes the amount of material for final disposal by order of magnitude (Green 1992). The most commonly utilised treatment practice for CW was incineration (Abd El-Salam 2010; Retnaraj et al. 2021). Some of the methods used to dispose of CW include chemical disinfection, wet thermal treatment, landfill disposal, and microwave irradiation (Retnaraj et al. 2021). The majority of hospitals depend on incineration to reduce their waste (Abd El-Salam 2010).

The incineration process of CW produced fly ash and bottom ash. The incineration process of CW produces two solid residuals: clinical waste incineration bottom ash (CWIBA) and clinical waste incineration fly ash (CWIFA). A proper incineration process of the waste material is required to reduce any harmful effects on human beings. In India, the incineration process involves the burning of collected CW into ash, which is then transferred to various landfill locations (Kaur et al. 2019). When the ash is deposited in landfills, therefore, hazardous metals and inorganic chemicals are discharged into the environment (Kaur et al. 2019). As a result, the cement-stabilization technique of waste treatment has become a widely used way of decreasing pollution and recycling wastes. The use of ash in construction goods has also become a popular method to reduce the amount of energy required to produce cement (Kaur et al. 2019). Besides, in Jordan, most CWs were incinerated to reduce the amount of landfill space required. Heavy metals, on the other hand, can be found in the ashes of incinerator waste, facing a secondary contamination problem that must be treated (Ababneh et al. 2020). Cement solidification is one of several methods for stabilising or removing heavy metals from ashes. CWIFA was pre-treated before being recycled as supplementary cementitious material in mortar mixes (Ababneh et al. 2020). After being collected from 252 health facilities in Istanbul, CW was burned at a daily rate of 35–40 tonnes. The ash from the rotary kiln is then disposed of in landfills. However, by the solidification/stabilisation (S/S) process, the potential for treatment and recycling of CWIBA was assessed (Akyildiz et al. 2017).

Solid wastes include any wastes that are generally solid in composition and are discarded as unusable or unwanted as a result of human and animal activity. The concept is broad in scope, encompassing both the heterogeneous volume of urban waste and the homogeneous accumulations of agricultural, industrial, and mineral wastes. Depending on its source, solid waste can be classified into the following categories: municipal Solid Waste (MSW) is categorized as household waste, CW or hospital waste is classified as infectious waste, and industrial waste is classified as hazardous waste. MSW includes household waste, construction and demolition debris, and sanitation residue. A large amount of MSW generated in Peninsular Malaysia increased from 16,200 tonnes per day in 2001 to 19,100 tonnes per day in 2005, or an average of 0.8 kg/capita/day (Tarmudi et al. 2009). The most significant environmental problem in Malaysia is highly dependent on landfilling as the primary disposal option to deal with the annual increase in solid waste generation annually (Moh and Abd Manaf 2016). As the world becomes more urbanised, solid waste management is becoming a major environmental and public health concern. The establishment of effective solid waste management systems in developing nations is interrupted by a variety of technological, financial, institutional, economic, and social problems (such as in Malaysia) (Ogawa 2011; Padfield et al. 2014).

Hazardous waste includes industrial and CW, which may contain toxic compounds (hazardous waste). The scheduled wastes increased 8.3 percent annually for the period 2015 until 2019, and 4013.2 tonnes were generated in 2019, Selangor recorded the higher scheduled waste of 1019.9 thousand tonnes in 2019 and also dominated the CW at 7.3 thousand tonnes as compared to other states (Prime Minister’s Department 2021). Hospital waste, sometimes known as CW, is formed during the diagnosis, treatment, or immunisation of
humans or animals, as well as during research procedures in these fields. Clinical activities generated toxic and potentially hazardous compounds at a higher number in the following decades, with waste generation increasing globally. Furthermore, waste caused by clinical activities is a significant issue in both natural and human environments. As a result, it’s possible that CW will be categorised as hazardous waste. All CW must be disposed of in the safest feasible manner for humans and the environment. Any solid and/or liquid waste, including its container and any intermediate product, generated during the diagnosis, treatment, or immunisation of humans or animals, or in related research, or in the manufacturing or testing thereof, is referred to as CW or hospital waste (Biswal 2013). Clinical or medical waste refers to all wastes generated during health care or diagnostic activities, and 75 percent to 90 percent of CWs are equivalent to domestic waste or municipal waste and pose no health risk (ICRC 2011). The physical, chemical, and biological properties of CW, as well as their toxicity and potential hazard, are all affected by the waste’s origin.

If CW is not managed correctly, it can be harmful to exposed populations and have adverse effects on the environment, water, soil, air quality, and human health. Metals in CW, in particular, may ultimately reach dangerous concentrations. Thus, it is essential to handle heavy metal simulated leachate effectively to protect groundwater (Manzoor and Sharma 2019; Racho and Jindal 2004). In a typical landfill state, municipal waste fly ash (MWFA) is often highly toxic, with high quantities of heavy metals and other substances that may easily leach into the ground or be discharged into the atmosphere. Furthermore, controlling MSW ashes has become one of the most challenging tasks because landfill practice encourages the likelihood of landfill leachates. (Al-Ghouti et al. 2021; Ivan Diaz-Loya et al. 2012). Besides, pollution of water supplies and soil-related to industrial solid waste leachate is being connected to several of the present illnesses that might cause anaemia and stomach cancer. The current practise of dumping ash near industrial zones of towns/cities has produced a severe environmental concern (Tiwari et al. 2015). Dumpsites damage the air, water, and groundwater, and toxicological symptoms are linked to dumpsite leachates. Whereby the dumpsites decrease the oxygen levels in the river, harming humans and aquatic life as well as associated adverse human effects such as acute lung cancer (Igbanoi et al. 2019; Iwuoha and Akinseye 2019). Seeds and seedlings can be utilised as acceptable biomarkers to measure industrial effluent toxicity (Iqbal 2016; Iqbal et al. 2019). Meanwhile, bioluminescence inhibition is beneficial for ecotoxicological screening and toxicity profiling (Abbas et al. 2018). The landfill conditions are necessary to determine the mobility of toxic contaminants and set limits to determine whether the material under scrutiny is toxic or not.

Omar et al. (2012) surveyed CW management practices in three Malaysian district hospitals and found several deficiencies, most notably in the segregation process. Guidelines on The Handling and Management of CWs in Malaysia (Department of Environment 2009) should be followed to ensure generation and minimisation, source separation and segregation, identification and labelling, handling and storage, and safe transportation. According to the report, the guideline should take into account occupational safety and health, public and environmental health, as well as research and development into enhanced technology and ecologically friendly practices. Lack of instructions on parts of CW segregation and practices by nurses, as well as overlapping of CW with general waste, are among the challenges facing hospitals. In addition, the concession company had to manage CW with additional operational costs. Waste minimisation and recycling, as well as alternate incinerator treatment technologies, are seen as major challenges (Razali and Ishak 2010). Al-Fares (2013) investigated the potential for CWIFA to be recycled and used in geo-environmental applications. The permeability values of CWIFA revealed little to no change, which will help to reduce the volume of CWIFA disposed of and limit potential risk. Furthermore, Ali Jawaid and Kaushik (2012) investigated the possibility of CWIFA S/S in geotechnical structures. Strength and leaching tests were used to determine the degree of effectiveness of the S/S product, and toxicity decreased as the strength of the S/S product increased. Meanwhile, Ababneh et al. (2020) investigated the fresh and hardened properties of CWIFA in mortar. The results showed that CWIFA additions had no effect on the workability of CWIFA in mortar, and the compressive and flexural strength values were acceptable up to 20% replacement. The results of the leaching tests showed that the heavy metals’ leachability was lowered below the EPA’s limitations. It was discovered that CWIFA has the potential to be utilised instead of being disposed of in landfills. The ash from the combustion has potential use in construction, and the leaching potential of CWIFA in terms of landfill safety and potential reuse should be further studied. The objectives of this paper is (I) to assess the clinical waste ash (CWA) generated by health-care activities through incineration process, (II) to identification physical–chemical characteristics of CW ash and examine the impact of CWIFA on compressive strength, (III) to provide an overview on the applications of CWIFA, and (IV) to present research progress in regard to related investigation the effect of discharge of CWA wastes on landfills and leaching behaviour of CWIFA.
Generation of Clinical Waste Ash (CWA)

CW quality will vary depending on the hospital and research facility's policies and processes, as well as the types of health care supplied. Malaysia generated 19,000 tonnes of waste per day in 2005, with a recycling rate of 5%. Despite an improved recycling rate of 17.5%, the quantity increased to 38,000 tonnes per day thirteen years later, in 2018. This is concerning because the rate surpassed the predicted rate of 30,000 tonnes per day in 2020 by the Japan International Cooperation Agency Research (Malaysian Investment Development Authority 2020). With limited landfill space and rising disposal prices, there is increased pressure and an urgent need to address the waste management problem and lessen its impact on the environment and the population's overall well-being. Kualiti Alam's hazardous waste solidification plant stabilises neutral inorganic waste and decreases the mobility of hazardous compounds in Malaysia. The plant can process 15,000 MT per year and treat 33,000 MT per year in 2021 (Aja et al. 2016; Cenviro Sdn. Bhd. 2021). Incineration, on the other hand, is being developed in Malaysia as a means of disposing of clinical and hazardous waste. Incineration is a systematic waste disposal method that is also one of the most costly. Incineration's creation, operation, and maintenance necessitate a significant financial investment as well as highly qualified employees (Moh and Abd Manaf 2016). As a result, to dispose of hazardous or CW, a proper waste management system should be necessary. Incineration, steam sterilisation, microwave sanitation, chemical disinfection, dry heat disinfection, and superheated steam disinfection are some of the procedures that have been used. However, incineration is the best available technology for disposing of CW (Jang et al. 2006; Rajor et al. 2012; Yong et al. 2009). Currently, 170 common CW treatment facilities with 140 incinerators are accessible around the country (Kumar et al. 2016; Rajor et al. 2012; Sathvik et al. 2019).

The incineration process destroys hazardous substances such as pathogens and toxic chemicals, reducing waste volume by 90% and weight by 75% (Ayilara et al. 2020; Stauffer and Spuhler 2010). The incineration process reliably and toxic chemicals destroy harmful substances such as pathogens, bacteria, viruses, prions, and the like, reducing waste volume by 90% and weight by 75% (Anicetus et al. 2020; Ayilara et al. 2020; Stauffer and Spuhler 2010). Incineration generally involves the combustion of mixed solid waste in the presence of air or sufficient oxygen. Typically, the temperature in the incinerator exceeds 850 °C, and the waste is transformed into carbon dioxide and water (Department for Environment Food & Rural Affairs 2013), resulting in the total destruction of any living organisms (Anicetus et al. 2020). Because the mixture contains CWIBA and CWIFA, hospital waste incineration not only emits harmful acid gases (CO, CO₂, NO₂, SO₂, etc.) into the atmosphere but also leaves a solid material called ash, which increases the amounts of heavy metals, inorganic salts, and organic compounds in the environment (Lombardi et al. 1998; Sharma and Sivapullaiah 2016; Sharma et al. 2013; Suresh et al. 2020; Zhao et al. 2009).

The majority of the ash produced is CWIBA, which is the residue that remains inside the burner after incineration. Post-burner equipment, such as scrubbers, collects CWIFA (Anamul 2012). When burned, CWA is melted at 1200 °C, the ash becomes molten, and the molten ash is transformed into slag by cooling at room temperature (Azni et al. 2005; Rajor et al. 2012). Heavy metals, inorganic salts, and organic chemicals in CWA may pose a concern to the environment and must be handled with caution to avoid contaminating ground water (Manzoor and Sharma 2019). According to data on the incineration facilities in Malaysia (Department of Environment 2020), data the burning of 39 883.32 MT/year of SW 404 (pathogenic, CWs, and quarantined materials) generates 6, 279.55 MT/year of ash (SW 406) across the country. Because of population growth and limited land area, the massive volume of ash generated yearly is a source of worry for landfill disposal. Toxic ash disposal in an environmentally friendly manner is difficult and costly. When handled properly, ash makes incineration prohibitively expensive for everyone, but when handled incorrectly, it causes both immediate and long-term health and environmental risks. The more effective the polluting trapping device in an incinerator is, the greater the quantity and toxicity of the leftovers. An incineration facility may discharge a hundred times more dioxin through ash than it does through air pollutants.

In Malaysia, health-care facilities are changing rapidly as facilities add and change activities each year to refocus and upgrade their operations. In Malaysia, CW is classified as scheduled waste under the Quality (Scheduled Waste) Regulations, 2005, including all groups and categories of CW that are collected and processed on-site from the same generation sources, which are SW404 and SW403 SW409, SW421, and SW410 (Pariatamby 2017). The ashes produced from the incinerator are also considered scheduled waste (SW406). Table 1 presents the quantity of CW generated in Malaysia from 2013 to 2020. The table shows that the amount of pathogenic waste, CWs, and quarantine materials increases with the increasing population and economy. Health-care service is improved, as is the development of specialised health services in hospitals and clinics and the growth of patients and awareness to manage the CW properly. However, the
quantities of the other wastes are inconsistent, depending on their use in the current year.

**Physical–Chemical Characteristics of CW Ash**

The CWIFA colour is greyish or dark grey (Ali Jawaid and Kaushik 2012; Anastasiadou et al. 2012). Table 2 shows the Physical Properties of CWIFA. However, compared to CWIBA, CWIBA was dark black or black (Al-Akhras et al. 2011; Anastasiadou et al. 2012). The specific gravity of CWIFA is 1.82 (Ali Jawaid and Kaushik 2012). Moisture content result of CWIFA is between 2.38 to 7.53% (Ali Jawaid and Kaushik 2012; Genazzini et al. 2003, 2005).

LOI of the CWIFA is between 3.60 to 31% (Al-Mutairi et al. 2004; Ali Jawaid and Kaushik 2012). The amount of delicate organic matter not wholly burning during the incineration process impact the proportion of LOI rises. The range of maximum and minimum particle size distribution of CWIFA is less than 2380 µm and less than 100 µm (Al-Fares 2013; Anastasiadou et al. 2012; Genazzini et al. 2003, 2005; Tzanakos et al. 2014). The X-ray fluorescence (XRF) analysis method was used to assess the significant elements and oxides of the CWIFA elemental composition and provide a qualitative identification and quantitative analysis of the component (Ababneh et al. 2020; Akyıldız et al. 2017; Anastasiadou et al. 2012; Tzanakos et al. 2014). The XRF analytical technique is used to determine the chemical structure of CWIFA by measuring the fluorescent X-ray released by a sample as a primary radiation source stimulates (Ababneh et al. 2020). Table 3 shows the chemical composition of CWIFA.

X-ray diffraction (XRD) is used in the research assessment and classification of mineralogical, crystalline, and leaching properties related to modifications to the main solid phases of CWIFA (Ababneh et al. 2020; Akyıldız et al. 2017; Anastasiadou et al. 2012; Tzanakos et al. 2014). The diffraction angle at the horizontal scale provides spacing to the crystal lattice and peak height at the vertical scale (Ababneh et al. 2020). The alite is a reactive crystalline phase, and it reduces the setting time of cement and increases the rate of early strength gain of concrete. Meanwhile, belite contributes to strength development at later ages (Rehman et al. 2020). Anhydrite affects the hydration of cement, and quartz acts as a filler, where calcite can stabilise ettringite,

### Table 1

| Year | SW 421 (MT/Year) | SW 424 (MT/Year) | SW 406 (MT/Year) | SW 404 (MT/Year) | SW 403 (MT/Year) |
|------|------------------|------------------|------------------|------------------|------------------|
| 2020 | 2,934.31         | 22.81            | 6,279.55         | 39,883.32        | 100,767.14       |
| 2019 | 5,589.70         | 6.32             | 2,948.81         | 33,756.99        | 471.20           |
| 2018 | 3,856.07         | 8.70             | 5,652.5          | 30,757.04        | 267.02           |
| 2017 | 3,389.63         | 12.23            | 976.34           | 28,375.24        | 458.97           |
| 2016 | 3,593.56         | 4.88             | 2,656.09         | 23,844.91        | 14,250.60        |
| 2015 | 1,654.47         | 2.35             | 3,618.54         | 25,523.33        | 282.31           |
| 2014 | 8,802.58         | 9.08             | 2,091.65         | 21,976.12        | 447.97           |
| 2013 | 19,083.09        | 1.07             | 2,231.85         | 18,152.95        | 1,470.14         |

SW421 A mixture of scheduled wastes, SW424 A mixture of scheduled and non-scheduled wastes, SW406 Clinker/slag/ashes from Incinerator, SW404 Pathogenic, CWs, and quarantined materials, SW403 Discarded drugs containing psychotropic substances or containing substances that are toxic, harmful, carcinogenic, mutagenic, or tetragenetic;

### Table 2

| Moisture content (%) | Specific gravity | Specific surface area (m²/g) | Particle size (µm) | Density (g/cm³) | Colour       |
|----------------------|------------------|-----------------------------|--------------------|-----------------|--------------|
| –                    | –                | –                           | <100               | –               | Greyish      |
| –                    | –                | –                           | <149               | –               | Dark grey    |
| –                    | 2.38             | 1.82                        | <120               | –               | –            |
| 7.53                 | –                | –                           | <2380              | –               | –            |
| 7.53                 | –                | –                           | <1000              | 2.5             | –            |
| –                    | –                | –                           | <2380              | 2.5             | –            |

SW421 A mixture of scheduled wastes, SW424 A mixture of scheduled and non-scheduled wastes, SW406 Clinker/slag/ashes from Incinerator, SW404 Pathogenic, CWs, and quarantined materials, SW403 Disposed drugs containing psychotropic substances or containing substances that are toxic, harmful, carcinogenic, mutagenic, or tetragenetic;
and gehlenite and periclase are carbonate minerals (Rehman et al. 2020). Based on studies, the main primarily crystalline substances mineral in CWIFA is calcite (CaCO₃), halite (NaCl), quartz (SiO₂), anhydrite (CaSO₄) and minor amounts of zeolite and thermonatrite (Anastasiadou et al. 2012; Sobiecka et al. 2014; Tzanakos et al. 2014). However, the CWIFA sample had highly complex mineralogy crystal structures also existed, such as CoFe₂O₄, CuMn₂O₄, and YCaAlO₄ (Ababneh et al. 2020). The other mineral is gehlenite (Ca₂Al(AlSiO₇), alite (Ca₃SiO₅), mullite (3Al₂O₃.2SiO₂), belite (Ca₂SiO₄), calcium chloride hydrate (Ca(ClO)₂•4H₂O), maghemite (Fe₃O₄), iron manganese titanium oxide (Fe₂MnTi₃O₁₀), and silicon titanium (TiSi₂), titanite (CaTiSiO₅) and perovskite (CaTiO₃) (Aubert et al. 2006; Rehman et al. 2020; Rodella et al. 2017; Akyıldız et al. 2017; Memon et al. 2013). The hydration of C–S–H gel and mono-sulfoaluminate crystals with hypothesised ball shapes and hexagonal layer shape factor of CWIFA impact the cement-based system (Ababneh et al. 2020). Meanwhile, Anastasiadou et al. (2012) only displayed a picture of the solidified CWIFA sample.

Figure 1 shows the SEM image of CWIFA before and after the solidification process. Studies on SEM image of municipal waste fly ash (MWFA) on solidified shows that the active silicon dioxide and aluminium oxide in MWFA take part in a pozzolanic reaction with Ca(OH)₂ produced from the hydration of cement (Yang et al. 2018). The hardened cement paste shows that C–S–H gel is formed in the hydration cement pastes cured for the third day (Yang et al. 2018). More C–S–H gel is produced with the delay of the hydration process for 28 days, leading to a denser microstructure of the products (Shi and Kan 2009a, b; Tang et al. 2016, 2020; Yang et al. 2018).

Tables 3 and 5 show the Metal Composition of CWIFA. Heavy metals concentrated in CWA trigger secondary contamination that requires care. CWIFA, a solid waste substance from CW incineration, typically includes mobile heavy metals and can cause significant pollution when reused. Much recent research on the usage of CWIFA has concentrated on mitigating their effects on the environment by analysing the leachability of heavy metals found in these products to enable their secure disposal in landfills or utilise as construction application materials. The standard requirement for removing CWIFA in dumpsite should be below the metal limit stated by the United States Environmental Protection Agency (USEPA), and the method to evaluate the metal in CWIFA content as toxicity characteristic leaching procedure (TCLP) SW 846 (IOWA Department of Natural Resources 2015).

Table 3 Chemical composition of CWIFA

| Constituent                  | (Ababneh et al. 2020) | (Tzanakos et al. 2014) | (Anastasiadou et al. 2012) | (Ali Jawaid & Kaushik, 2012) | (Genazzini et al. 2005) | (Al-Mutairi et al. 2004) | (Genazzini et al. 2003) |
|------------------------------|-----------------------|------------------------|-----------------------------|-----------------------------|-------------------------|--------------------------|-------------------------|
| Silicon oxide (SiO₂) %       | 16.58                 | 6.0                    | 6.0                         | –                          | 0.39                    | –                        | 0.39                    |
| Aluminium oxide (Al₂O₃) %    | –                     | –                      | –                           | –                          | 14.34                   | –                        | 14.34                   |
| Iron oxide (Fe₂O₃) %         | 52.71                 | 0.3                    | 0.3                         | –                          | 4.64                    | –                        | 4.64                    |
| Magnesium oxide (MgO) %      | 0.34                  | 1                      | 1                           | –                          | 2.81                    | –                        | 2.81                    |
| Calcium oxide (CaO) %        | 1.64                  | 89.2                   | 89.2                        | –                          | 33.18                   | –                        | 33.18                   |
| Potassium oxide (K₂O) %      | 0.37                  | –                      | –                           | –                          | 0.6                     | –                        | 0.6                     |
| Sodium oxide (Na₂O) %        | 7.4                   | 2.5                    | 2.5                         | –                          | 3.64                    | –                        | 3.64                    |
| Others (%)                   | 0.65                  | –                      | –                           | –                          | –                       | –                        | –                       |
| Loss of ignition (LOI) %     | –                     | –                      | –                           | –                          | –                       | –                        | –                       |
| (SiO₂ + Al₂O₃ + Fe₂O₃) %      | 69.29                 | 6.3                    | 6.3                         | 0                          | 19.37                   | 0                        | 19.37                   |

* (SiO₂ + Al₂O₃ + Fe₂O₃) = 69.29%
test (Anastasiadou et al. 2012; Tzanakos et al. 2014). The CWIFA TCLP leachates had high concentrations of Zn (13.2 mg/l) and Pb (5.21 mg/l) and lower levels of chromium (Cr), iron (Fe), nickel (Ni), copper (Cu), cadmium (Cd) and barium (Ba) (Anastasiadou et al. 2012; Tzanakos et al. 2014). There is a high proportion of heavy metals in raw
MWFA (Qian et al. 2006; Yang et al. 2018). Leaching heavy metals of MWFA such as Zn, Cr, Cu, Pb, and Cd is much lower than the Taiwan Environmental Protection Agency regulatory thresholds (Bie et al. 2016; Lee 2009; Shi and Kan 2009a). The heavy metals concentration of MWFA comprises a substantial increase with an increased amount of MWFA (Yan et al. 2019). The content of heavy metals in the MWFA differed dramatically from one city to another. The concentrations of MWFA depend on the combustion system and seasonal and regional differences in the world (Qian et al. 2008). Table 2 shows the metal composition of raw CWIFA.

Mechanical Properties

The mechanical properties of CWIFA in mortar were investigated to study the compressive strength. Several studies were published examining the impact of CWIFA on compressive strength. Compressive strength of the solidified matrix developed for all blends and control material with increasing curing time. The cement content decrease in the cement mix with CWIFA is primarily responsible for decreasing strength (Ababneh et al. 2020; Al-Mutairi et al. 2004; Anastasiadou et al. 2012; Genazzini et al. 2005; Lombardi et al. 1998). Moreover, the inclusion of CWIFA and calcium carbonate allowed the geopolymer matrices' compressive strength to increase dramatically (Tzanakos et al. 2014). Besides, the compressive strength of the samples applied with activated carbon (AC) and rice hush was marginally lower than that of samples solidified with cement alone (Agamuthu and Chitra 2009). The compressive strength of the waste matrices was higher for the samples treated and solidified with OPC, followed by the samples treated with Mascrete cement and ground granulated blast furnace slag (Agamuthu and Chitra 2009).

The compressive strength for 60% cement combined with 40% CWIFA is 2.52–12.70 MPa (Anastasiadou et al. 2012). Table 6 shows the Compressive strength and findings of CWIFA. The total compressive strength values were between 0.70–7.63 MPa for all geopolymers mixtures (Tzanakos et al. 2014). The compressive strength values meet the standard stipulated for the solidified waste material needed in the landfill for disposal, which after 28 days is 0.414 MPa (Anastasiadou et al. 2012; Lombardi et al. 1998; Qian et al. 2006). The study on the compressive strength of MWFA on mortar shows that with 10% MWFA, the mechanical properties of MWFA in cement matrices are gradually reduced at 28 days (Rehman et al. 2020; Shi and Kan 2009b). The compressive strength of MWFA increased after one day of casting, indicating that MWFA was helpful in securing high early stability (Rehman et al. 2020). When mixing with 50% MWFA and curing for 28 days, the compressive strength reduces from 40.0 MPa to 11.52 MPa (Bie et al. 2016). The mechanical strength of higher replacement of MWFA is controlled below 40% according to Chinese National Standard GB 175–2007 (Yang et al. 2018). The compressive strength decreased with the rise in the percentage amount of CWIFA due to the substitution of cement (higher CaO and SiO2 content) with CWIFA with a lower CaO and SiO2 range (Ababneh et al. 2020). The MWFA had a comparatively low cementitious impact that could slow down cement hydration, and when mixed with a higher amount of MWFA, its significantly compressive strength decreased (Bie et al. 2016; Shi and Kan 2009a; Tang et al. 2016; Yang et al. 2018). Also, longer curing times have a beneficial impact on S/S products (Lombardi et al. 1998). The compressive strength of the mixtures improved with the increase in the cement/MWFA ratio and curing time, resulting in the pozzolanic reaction and fixation of water molecules (Bie et al. 2016; Shi and Kan 2009a; Tang et al. 2016; Yang et al. 2018).

### Table 5: Metal composition (TCLP hazardous waste limit) of CWIFA

| Hazardous waste criteria | **TCLP Hazardous waste limit (mg/l)** | (Tzanakos et al. 2014) | (Anastasiadou et al. 2012) | (Genazzini et al. 2003) |
|--------------------------|--------------------------------------|------------------------|---------------------------|------------------------|
| Cadmium (Cd)             | 1.0 (mg/l)                           | < DL                   | 0.0171                    | 0.04                   |
| Lead (Pb)                | 5.0 (mg/l)                           | 6.0172                 | 5.2162                    | 0.9                    |
| Zinc (Zn)                | –                                    | 0.1865                 | 0.0855                    | 0.2                    |
| Chromium (Cr)            | 5.0 (mg/l)                           | –                      | 1.03                      | 0.1                    |
| Copper (Cu)              | –                                    | –                      | 0.0762                    | –                      |
| Nickel (Ni)              | –                                    | < DL                   |                           |                        |

**TCLP is a test to determine contaminants' mobility in solid wastes or soils. These limits are allowed to leach out of soil or solid waste in a landfill from 40 CFR 261.24 (IOWA Department of Natural Resources 2015)**
| Author's | Types of cement-based system | CWIFA Replacement material as | Water/cementitious (W/C) ratio | Other material added | Percentage of CWIFA Replacement (%) | Result Compressive Strength (7 Days) MPa | Result Compressive Strength (28 Days) MPa | Finding |
|----------|-----------------------------|------------------------------|-------------------------------|---------------------|--------------------------------------|--------------------------------------------|--------------------------------------------|---------|
| (Ababneh et al., 2020) | Mortar | Cement | 0.55 | 0.5% Nano silica | 0% Raw CWIFA | – | 30.4 | The addition of nano-silica increases early compressive strength |
| | | | | | 5% Raw CWIFA | 21.2 | | |
| | | | | | 10% Raw CWIFA | 21.1 | | |
| | | | | | 15% Raw CWIFA | 19 | | |
| | | | | | 20% Raw CWIFA | 18.1 | | |
| | | | | | 0% Treated CWIFA | 30.4 | | |
| | | | | | 5% Treated CWIFA | 25.8 | | |
| | | | | | 10% Treated CWIFA | 22.5 | | |
| | | | | | 15% Treated CWIFA | 21 | | |
| | | | | | 20% Treated CWIFA | 19.7 | | |
| (Tzanakos et al., 2014) | Geopolymers | Cement | – | 75% CWIBA | 20% (mixed 25% CWIFA + 75% CWIBA) | *0.9 | *1.2 | The inclusion of CWIFA and calcium carbonate increase the compressive strength |
| | | | | | 30% (mixed 25% CWIFA + 75% CWIBA) | *1.5 | *2.3 | |
| | | | | | 50% (mixed 25% CWIFA + 75% CWIBA) | *2.2 | *3.2 | |
| | | | | | 50% CWIBA | 20% (mixed 25% CWIFA + 50% CWIBA) | *2.0 | *2.4 | |
| | | | | | 30% (mixed 25% CWIFA + 50% CWIBA) | *2.5 | *3.6 | |
| | | | | | 50% (mixed 25% CWIFA + 50% CWIBA) | *3.3 | *4.9 | |
| | | | | | 30% (mixed 25% CWIFA + 75% CWIBA) | *2.2 | *3.2 | |
| | (Anastasiadou et al., 2012) | S/S | Cement | – | – | 0% CWIFA | – | 32.3 | The compressive strength was reduced as the percentage of cement was reduced |
| | | | | | 40% CWIFA | 12.70 | | |
| | | | | | 50% CWIFA | *4.0 | | |
| | | | | | 60% CWIFA | *1.5 | | |
| | | | | | 70% CWIFA | 1.3 | | |
| Author's                        | Types of cement-based system | CWIFA Replacement material as | Water/cementitious (W/C) ratio | Other material added | Percentage of CWIFA Replacement (%) | Result Compressive Strength (7 Days) MPa | Result Compressive Strength (28 Days) MPa | Finding                                                                 |
|--------------------------------|------------------------------|------------------------------|--------------------------------|----------------------|-------------------------------------|------------------------------------------|------------------------------------------|--------------------------------------------------------------------------------|
| (Agamuthu & Chitra, 2009)     | S/S Cement                   | Cement                       | –                              | -                    | CWIFA – Mascrete cement 70%, 60%, 50% and 40% | Between 0.6 – 1.8                         | Between 0.6 – 1.8                         | The compressive strength with AC and RH was lower than solidified with cement alone |
|                                |                              |                              |                                |                      | Activated carbon                   | Between 0 – 1.9                           | Between 0 – 1.9                           |                                                                                  |
|                                |                              |                              |                                |                      | Rice husk                          | Between 0.5 – 1.9                         | Between 0.5 – 1.9                         |                                                                                  |
|                                |                              |                              |                                |                      | GGBS                                | Between 0 – 0.7                           | Between 0 – 0.7                           |                                                                                  |
|                                |                              |                              |                                |                      | Activated carbon and GGBS          | Between 0 – 0.9                           | Between 0 – 0.9                           |                                                                                  |
|                                |                              |                              |                                |                      | Rice husk and GGBS                 | 0.3 – 0.8                                 | Between 0.3 – 0.8                         |                                                                                  |
| (Genazzini et al., 2005)       | Mortar Cement                | 0.55                         | –                              | 0% CWIFA 1% CWIFA 25% CWIFA 50% CWIFA | –                                   | 38.8                                     | 26.2                                      | The lower strength development of the mortar as CWIFA increases                   |
|                                |                              |                              |                                |                      |                                     |                                          |                                          |                                                                                  |
### Table 6 (continued)

| Author's                  | Types of cement-based system | CWIFA Replacement material as | Water/cementitious (W/C) ratio | Other material added | Percentage of CWIFA Replacement (%) | Result Compressive Strength (7 Days) MPa | Result Compressive Strength (28 Days) MPa | Finding                                                                 |
|---------------------------|------------------------------|-------------------------------|-------------------------------|---------------------|-------------------------------------|------------------------------------------|------------------------------------------|--------------------------------------------------------------------------------|
| (Genazzini et al. 2003)   | Mortar                       | Cement                        | 0.35, 0.5                     | –                   | 0% CWIFA (w/\(c + a = 0.35\))       | 56.6                                     | 26.2                                     | The lower strength development of the mortar as CWIFA increases |
|                           |                              |                               |                               |                     | 10% CWIFA (w/\(c + a = 0.35\))      | 26.2                                     |                                          |                                                                                               |
|                           |                              |                               |                               |                     | 25% CWIFA (w/\(c + a = 0.35\))      | 17.6                                     |                                          |                                                                                               |
|                           |                              |                               |                               |                     | 50% CWIFA (w/\(c + a = 0.35\))      | 14.0                                     |                                          |                                                                                               |
|                           |                              |                               |                               |                     | 0% CWIFA (w/\(c + a = 0.35\))       | 39.9                                     |                                          |                                                                                               |
|                           |                              |                               |                               |                     | 10% CWIFA (w/\(c + a = 0.35\))      | 20.1                                     |                                          |                                                                                               |
|                           |                              |                               |                               |                     | 25% CWIFA (w/\(c + a = 0.35\))      | 11.7                                     |                                          |                                                                                               |
|                           |                              |                               |                               |                     | 50% CWIFA (w/\(c + a = 0.35\))      | 8.9                                      |                                          |                                                                                               |

*Approximate from the graph by previous research*
Applications

In Concrete

Al-Mutairi et al. (2004) evaluated the effects of hospital ash, and micro silica on concrete compressive strength at various temperatures, comparing the compressive strength of ash mixes to that of micro silica and normal concrete to determine their effectiveness. In general, replacing 5% of the cement with micro silica or CWIFA enhances the compressive strength of concrete up to 800 °C. However, it has the lowest compressive strength of all concrete types, up to 15%. Meanwhile, replacing cement with CWIBA had no effect on compressive strength; however, CWIFA or micro silica, on the other hand, makes concrete stronger.

According to Rehman et al. (2020), concrete 3D printing is a 3D printing application that uses MWFA as a substitute for ordinary Portland cement to create a rapid method for building without the requirement of formwork. The findings revealed that the MWFA's setup time improving effect and initial yield stress enhancement enabled a rapid construction. Meanwhile, Yan et al. (2019) explored MSWFA as a partial replacement for Portland cement, finding that the pozzolanic interaction between MSWFA and cement improved the mechanical properties of cement-stabilized macadam (CSM), which included 25% MSWFA. In addition, after 7 days of curing, the concentration of heavy metals in CSM, including MSWFA, was lower than the Chinese Standard. Meanwhile, Shi and Kan (2009a, b) investigated the use of MWFA as supplementary cementitious material in concrete mixes and discovered that while the MWFA has some cementitious activity but its reactivity is low. Its addition to cement may cause cement hydration to be delayed. However, the mechanical properties of MWFA in cement matrices decrease with increasing MWFA. According to Shi and Kan (2009a), cement effectively immobilises MWFA, and most leached heavy metals are created at an early age. Besides, heavy metals' diffusion coefficients decrease with the delay of age, and MWFA is likely to be used as a partial replacement for cementitious material in concrete mixes. Aubert et al. (2004) investigated if MWFA in concrete behaves similarly to sand, and the results suggest that incorporating MWFA in concrete could be a way to add value. Using MWFA instead of cement in concrete does not result in a more significant loss of mechanical strength than reducing the cement content, and it is permitted for road use.

According to Prasanth and Ranga Rao (2019), using 20% CWIBA and 20% Metakaolin increased the compressive and split tensile strength of M30 grade concrete at 28 days compared to control concrete. Kaur et al. (2019) investigates the impact of CWIBA as a fine aggregate replacement on concrete strength and permeability, and CWIBA range in a wide variety of particle sizes, making it ideal for usage as a concrete filler. CWIBA can be used to replace up to 10% of fine aggregate (sand) in concrete without affecting the strength. The addition of CWIBA to concrete reduces its workability, requiring the use of a superplasticizer to make CWIBA concrete workable. Furthermore, the results of the solidified matrix revealed that cement was capable of immobilising heavy metal leaching. Meanwhile, the CWIBA ratio was found by Akyildiz et al. (2017) to reduce concrete compressive strength. The compressive strength of 50% cement with 50% CWIBA lowers to 11.3 MPa, compared to 38 MPa for 100% cement with 0% CWIBA. As a result, the CWIBA mixing ratio of 15% was ideal for efficient application in construction. During the TCLP test, the high metal concentrations were S/S, and the leaching heavy metal concentrations were within the legal limits for landfilling, so the waste was classified as non-hazardous.

Bala and Musa (2017) examine the flexural strength of concrete beams using CWA instead of cement. The CWA utilised in the study had a pozzolanic activity index of 85.97%, above the ASTM requirement of 70%. Although density and water absorption increase with replacement level and curing age, the composite mix's workability decreased after 10% replacement. Substituting CWA for concrete lowers the flexural strength value, making hospital waste Ash is a durable construction material used in concrete manufacturing. Elinwa (2016) investigated that the CWA had a high CaO content (47%), making it suitable for cement production. Besides, concrete cubes were made with CWA proportions varying from 0 to 40% by weight of cement, and the ideal replacement is 10%. The compressive strength of concrete decreases with the increase replacement of CWA, because CWA lowers concrete workability and must be combined with a plasticizer. Meanwhile, CWA is pozzolanic, it may be utilised as a heat retarder, and CWA is a concrete additive. Memon et al. (2013) investigate the usage of Pakistani hospital waste ash as a cement alternative. CWA can be used as a partial replacement for cement in concrete without affecting the strength. The addition of CWA to the mix increased setting time while decreasing density and water absorption.

In Portland Cement Mortars

Most concretes nowadays have mineral additions like pozollans, fly ash and silica smoke, blowing slack, etc. The ability to incorporate cement-based materials into the CWIFA is presented here. An analysis was carried out by Ababneh et al. (2020) on a partial cement substitution of CWIFA with different proportions of 0 to 20% in terms of cement weight. Silica nanoparticles have been added to the mixture to facilitate early strength development. Test results of
leaching showed that heavy metals' leachability was lower than the USEPA limit. CWIFA did not significantly influence CWIFA mortars' workability, and up to 20% was good compressive strength and flexural strength values (Ababneh et al. 2020). Genazzini et al. (2003) investigated that CWIFA characterisation was performed by chemical analysis, X-ray diffraction, radioactive material detection, and fineness and density tests. Portland cement systems can be an option for the disposal of these kinds of ashes, and mortars are prepared to contain up to 50% of cement (Genazzini et al. 2003). In the study, Al-Akhras (2011) investigates the stabilisation of CWA in mortar mixtures by three CWA dosages: 5%, 10%, and 15%. The proportions of the mortar mixture are 1:3:0.7 for cement, sand, and water by weight. Without significant leaching of heavy metals, CWA can be stabilised in mortar mixtures. With the rise in CWA content, the setting time of cement paste declined. When the CWA level was raised, mortar workability improved (Al-Akhras et al. 2011). The compressive strength of the mortar, however, decreased as the CWA content increased. After 28 days of immersion in water, the number of heavy metals leached from mortar specimens was very small and negligible (maximum percentage of 0.58%) compared to the original heavy metals present in the CWA powder (Al-Akhras et al. 2011).

Bie et al. (2016) investigated the curing duration and heavy metal leaching content of MWFA mortar specimens and showed that MWFA decreased the mortar sample's strength. Heavy metal leaching concentrations, particularly Pb and Cd, dropped significantly after combined MWFA and cement. Furthermore, as the PH increased, the heavy metal concentration in the leaching liquid decreased dramatically, but the heavy metal concentration increased with leaching vibrating time (16 or 32 h). To prevent pollution from waste incineration and chemical–mechanical polishing, Lee (2009) suggested utilising MWFA in masonry. Nanoparticle activation and hydration create quick strengthening, and polluting leachates from these modified cement mortars were minimal. The MWFA slag and chemical–mechanical polishing sludge mortar excelled over the OPC mortar in compressive strength and workability, potentially expanding the improved mortar's civil engineering applications.

**In Cement-Based Materials as Containment Systems**

In the last few decades, waste generation has proliferated around the world. In turn, incineration is an alternative way to minimise waste volume, which results in ash being generated as a new kind of waste. For potential uses in construction materials, the new cement-ash composite method was tested—the addition of CWA in cement matrices that can be used as building components. Tzanakos et al. (2014) investigated the use of CWIFA as a raw material for geopolymer production and the cure of geopolymers at 50 °C within 24 h. The strength of geopolymer specimens, heavy metal leachability, mineralogical process, and the effects of CWIFA addition and compounds of calcium were investigated by Tzanakos et al. (2014) after a specific ageing period of 7 and 28 days. The addition of calcium compounds greatly increases the strength of specimens of geopolymers (2–8 MPa) and decreases heavy metals (Tzanakos et al. 2014). The mechanical characteristics of the CWIBA, which can be applied as a binder with different quantities of Ordinary Portland Cement (OPC) were studied by Anastasiadou et al. (2012). The cement-based solidification strength was 0.55–16.12 MPa and decreased with cement loads reduction (Anastasiadou et al. 2012). Cement can immobilise the CWIFA and CWIBA heavy metals. TCLP raw CWIFA leachates contain high Zn and Pb concentrations and less Cr, Fe, Ni, Cu, Cd, Ba, and other leachates (Anastasiadou et al. 2012). Agamuthu and Chitra (2009) have reviewed alternative therapies of CWIFA using three forms of cement: OPC, MSC, and GGBS by solidifying/stabilising (S/S). The CWIFA had high Al, Ti, Fe, Zn, and Cr concentrations, and most of these elements were heavily leached if not treated. Carbon-activated additives (Ac) and rice husk (Rh) were 10, and 20% reduced leached metals (Agamuthu and Chitra 2009). Compressive strength improved with increased cement loading and curing days, and greater efficiency in metal retention and compressive strength was demonstrated by OPC. CWIFA goods may be used as building raw materials (Agamuthu and Chitra 2009). Genazzini et al. (2005) examined that incineration became an alternative for reducing waste volume, leading to the generation of CWIFA as a new type of waste.

For inertizing ash from hospital solid waste incineration, Lombardi et al. (1998) evaluated the mechanical and leaching characteristics of the Portland Cement-based S/S method. Heavy metals (Cd, Cu, Ni, Pb, and Zn) are strongly immobilised by the cementitious matrix after curing in tap water at 20°C. Thus, S/S materials can be dumped in landfills with less environmental protection than untreated waste. CWIFA addition was potentially for building elements in cement matrices. Genazzini et al. (2005) researched to determine the incorporation of CWIFA in cement matrices for future building applications and concluded that CWIFA might be used in masonry blocks. However, because of the metal leachability demonstrated with spiked ash, it’s critical to look into the composition and performance of CWIFA before using it in cementitious matrices. Sobiecka et al. (2014) found that adding Portland cement to CWIFA increased its stability utilising two S/S procedures: hydration and granulation, with cement hydration producing more stable products. The CWIFA to Portland cement ratio stabilised the solidified product, forming a calcium silicate
hydrate gel on the surface of the stabilised samples. A 50 percent CWIFA/Portland cement mix produced the most stable C–S–H gels. The leachability of six heavy metals is also affected by the pH of surrounding fluids, with the lowest leachability values found at pH 7–8. Rozumová et al. (2015) evaluated three different amounts of cement admixture (10%, 20%, and 30%) and four different solidification durations to investigate the solidification of CWIBA from hazardous waste incineration (1 day, 4 days, 7 days, and 28 days). The ideal combination is a 30 percent cement addition and a 28-day solidification period; however, increasing cement quantity and solidification period do not always minimise pollutant mobility. The majority of the elements/compounds were stabilised using cement; nevertheless, the cement utilised was found to be unsuitable for treating the hazardous waste under investigation, at least when consolidated for 28 days. Filipponi et al. (2003) explored CWIBA and Portland cement in cement-based composites, establishing mixtures by varying the amounts of CWIBA and Portland cement with water. A two-way repeated factorial design was used to investigate the characteristics of solidified CWIBA–Portland cement mixes and the importance of improving CWIBA reactivity, either by increasing its specific surface area or using chemical activators capable of promoting pozzolanic reactions, was emphasised.

The S/S of MWFA containing heavy metals using the cement of Portland as a binder was investigated by Tang et al. (2016) and found that there is a significant mechanical (i.e., compressive strength) and leaching activity of MWFA blends concerning the cement/fly ash ratio and the curing period. The presence of cement results in lower leaching resulting from ettringite formation and a limitation of the migration of heavy metal ions. The lower cement/MWFA and lower curing time of the compressive strength can be due to the increase in the MWFA loading, preventing the development of hydration products and destroying the structure of the products (Tang et al. 2016). Yang et al. (2018) researched the feasibility of municipal waste ash application as additional cement preparation material for municipal waste incineration. The 10–50% cement composites were replaced with municipal waste ash. The cementitious activity of washed municipal waste ash has some cementitious activity. However, the activity is relatively lower than in Portland cement (Yang et al. 2018). The addition of washed municipal waste ash was found to have a deleterious effect on the mechanical strength of cement composites. The maximum replacement was limited to 40 wt% and 20 wt% (Yang et al. 2018). It was found that the recycling of MWFA for cement production can achieve a significant economic and environmental benefit at the same time.

Geotechnical and Geo-Environmental Application

To eliminate/reduce the existence of unacceptable toxic elements in a geotechnical system, Ali Jawaid and Kaushik (2012) investigate the possibility of CWIFA S/S by reduction of toxicity with an improvement in S/S product strength. A high concentration of heavy metals like lead is presented in the stabilised soil with 20% of CWIFA (Ali Jawaid and Kaushik 2012). The S/S soil leachate analysis—CWIFA mix of cement (20%) confirms heavy metals encapsulation. The concentration of lead (Pb) is also within the permitted 0.1 mg/l limits. S/S soil-CWIFA mix with 20% cement is the broad-scale application of CWIFA for geotechnical constructions (Ali Jawaid and Kaushik 2012). In assessing the efficacy of recycling CWA, the permeability and compaction properties of soil—CWIFA mixtures made with different CWIFA percentages are compared by Al-Fares (2013). The CWIFA is combined with an in-situ residual weathered and degraded weakly cemented calcareous/gypsiferous silty sandstone material known in the region as Gatch for potential future use in geo-environmental applications (Al-Fares 2013). The Gatch samples were then applied to CWIFA in various percentages (0%, 0.1%, 1%, 2.5%, and 5% with dry soil weight). As the percentage increased for CWIFA, the permeability of CWIFA-Gatch blends decreased to 1%, a point where there was little to no substantial improvement in permeability values in any additional increments in CWIFA material.

In Agriculture

CWA can be used in agriculture because it contains nearly all biological carbon and nitrogen macro and micronutrients. It can help increase productivity in different agricultural crops as a chemical fertiliser. Fenugreek and Mustard were treated with various doses of ash, cow dung, urea, and superphosphate (Goswami-Giri 2007). The effect of these fertilisers varies according to the crop type and the soil type. On the average growth of Fenugreek and Mustard, the positive impact of ash was observed. Compared to regulation, the yields of Fenugreek and Mustard are up by about 54% to 55% and 35%, respectively, and 1.0 gm and 1.5 gm of ash were added in all treatments, respectively (Goswami-Giri 2007). Reusing ashes has the potential to reduce the demand for commercial fertilisers, contribute to pH remediation, and help to solve the ash disposal problem. The previous study has shown that ash wastes include earth elements including Si, Al, K, Ca, and Mg, as well as micronutrients essential for plant development. Meanwhile, because of their high pH, ash wastes may be beneficial as a liming agent. Incinerator ash can be used as a liming agent.
on acidic soil and may have agronomic benefits. However, the amount of ashes that may be placed on agricultural land is limited due to the heavy metal content. These are because the high levels of trace metals can induce phytotoxicity as well as human and animal health issues (Zhang et al. 2001, 2002). The MSWIFA has a high pH and can thus replace lime in decreasing soil acidity. Due to the noticeable large quantities of soluble salts in the ash, adding MSWIFA to the soil will almost certainly increase its salt content. These salts are problematic because they can cause plant salt stress (Ferreira et al. 2003). Meanwhile, MSWIBA may include beneficial elements such as calcium, which can effectively influence plant development. In greenhouse pot experiments, no significant difference was seen between test plants grown with MSWIBA and those planted in commercially prepared growing media (Sormunen et al. 2016).

As a Road and Asphalt Stabilising Agent

The CW is incinerated and then melted at 1200 °C in Selangor, Malaysia. Scanning electron microscope (SEM) shows that the waste incinerator in hospitals created after melting the ash incinerator contained over 53%, 9%, and 16%, respectively, of SiO₂, CaO, and Al₂O₃ (Azni et al. 2005). The slag leaching showed the effective stabilisation of heavy metals through the melting process, and the slag could serve as a replacement for typical road construction aggregates. The findings from mixing experiments with aggregates and asphalt have shown that the slag meets all the alternative unit criteria. Azni et al. (2005) also tested the suitability of using molten slag as a thin-film oven test. Molten slag had an aggregate crushing value of 15.94%. This value provides a relative measure of the aggregate’s resistance to crushing under a slowly increasing load. The aggregate’s toughness to resist fractures was 29.82 percent, which also met the minimum level. Angularity number is an important feature because it affects the functionality and stability of an asphalt mixture. More angular aggregates ensure good interlocking, stability, and durability. CW slag was also ideal for use as a substitution agent (Azni et al. 2005).

The Effect of Discharge of CWA Wastes on Landfills

Leachate is the liquid created when waste decomposes in a landfill and water filters through it. This liquid is very toxic and can potentially damage land, groundwater, and waterways. The most common method of disposing of CW ashes is to transfer them to a landfill and bury it. As a result, disposal at landfill sites with landfill cover is a systematic method of managing MSW ashes. In contrast, the disposal of CW ashes at a disposal facility is a secured landfill (He et al. 2017). Heavy metal concentration in soils from a waste dump may be caused by inadequate protection of the area surrounding the dump. As a result, heavy metal leaching and migration to groundwater and surface flows might threaten the aquatic environment and plant cover (Twaróg et al. 2020). The TCLP of CWA S/S heavy metal leachate can fulfil the quality criteria for landfill discharge (Suryawan et al. 2019). Furthermore, dumping MSW in a landfill produces odours, methane gas, and a variety of other hazardous and reactive substances. Because waste-to-energy ash is biologically inactive, it produces no odours or explosive, poisonous, or reactive gases from the landfill. Landfilling is the usual solution for wastes that have no other option, and MSW ash is now primarily used as a landfill structural material (Joseph et al. 2018). Furthermore, groundwater contamination from a raw MSW landfill is substantially lower than that from an ash dump since ash leaching is largely inorganic, can be confined with a simple liner (drainage) system, and is not challenging to remediate. The environmental consequences of using MSW ashes as a substitute for natural materials in landfill cover designs. Water draining off the landfill cover (leachate) was polluted with easily leachable species such as Cl and nitrogen. The projected reduction in leachate pH may result in enhanced leaching of, for example, Ni and Zn from the ashes (Travar et al. 2009). Landfills incorporate environmental protections such as a barrier layer and a leachate recovery system. The primary application of MWFA is as a landfill cover, which can reduce the size of the landfill site (Sun et al. 2016). The use of MWFA in a landfill top cover is usually seen as a beneficial ash management strategy, and MWFA might be regarded as a suitable liner material for landfill top covers. The ageing of ash in the landfill top cover may result in less leaching and a large reduction in Cl leaching (Brännvall and Kumpiene 2016). Because leachate from the ash cover is likely to have a minor effect on overall landfill leachate quality the landfill operator must install a top cover after closure for both municipal and hazardous waste landfills (Pasupathi et al. 2011). Meanwhile, wastewater contains organic compounds, ammoniacal nitrogen, inorganic salts, chlorinated organics, and heavy metals, and leachate or landfill effluent must be cleaned before being discharged to protect the environment. The usage of low-cost media may help to ensure the sustainability of the environment (Rosli et al. 2019). Agriculture, mining, household, and industrial wastewater create environmental damage, and adsorbents pore sizes help absorb zinc from Palm oil mill effluent (POME) (Adeleke et al. 2017). Because it can tolerate low-concentration contaminants, adsorption is superior to other wastewater treatment techniques (Adeleke et al. 2019). The overall kinetics of adsorption revealed that utilizing a bone-biocomposite to reduce chemical oxygen demand (COD) from POME was efficient at the first stage of adsorption (Adeleke et al. 2021a, b). The biosorption process was regulated by electrostatic interaction and hydrogen bonding such that acid-treated durian peels may be employed as an
alternative biosorbent for the treatment of textile and dyeing industry effluents (Adeleke et al. 2021a, b). Zeolite is a low cost and ecologically benign substance capable of removing ammonia nitrogen from natural rubber effluent with over 80 percent effectiveness (Nasir et al. 2019). Thus, while implementing solutions to mitigate environmental consequences, leachate collection and treatment for landfills should be prioritised. To achieve this, the real polluting impact of leachate should be determined.

Leachate Analysis—Leaching Behaviour of CWIFA in Mortar (TCLP, 1311)

Leaching is the term used in environmental applications to describe the release of potentially harmful substances. Assessing the leaching of contaminants into groundwater is one of the primary pathways for evaluating the danger of solid wastes on human health and the environment. Leachate is a liquid that flows from a landfill after the garbage has been leached. Its composition varies greatly depending on the age of the landfill and the waste it contains. Landfill sites that are correctly built and engineered can reduce the risk of leachate generation. Garcia-Lodeiro et al. (2016) studied leachate analysis of MSW incineration fly ash and bottom ash as cement. They showed that heavy elements are immobilised due to physical encapsulation or chemical interaction with the cementitious gel in the host matrix.

When utilising a CWIFA in mortar, the primary environmental concern is if any harmful materials leach out during the initial curing process or throughout the life of the mortar. Once again, the TCLP is the most often utilised procedure for determining whether a substance can be labelled as non-toxic. The TCLP was used to assess the mobility of organic and inorganic waste in liquid, solid, and multiphase phases. TCLP analysis of all CWIFA specimens found amounts of heavy metals below regulatory limits (Anastasiadou et al. 2012; Tzanakos et al. 2014). The determination of leachate concentrations is frequently employed as a compliance criterion for measuring wastes toxicity. Apart from analysing environmental quality, the leaching behaviour study can be utilised to investigate the binding mechanisms and durability of features of composite cement-based systems. The leaching behaviour of waste-containing cement-based systems has been extensively investigated due to the widespread usage of cement-based systems to immobilise metals or other pollutants. The most fundamental process by which cement-based systems containing waste products can damage the environment is through hazardous leaching metals. The amount of heavy metals leached is negligible compared to the total amount of heavy metals present in CWA powder. However, in practice, the mortar will remain wet for a shorter period but more frequently during rainy occurrences (Al-Akhras et al. 2011).

S/S is the treatment method used to reduce the leachability of the heavy metals present in such products. S/S is accepted as a well-established disposal technique for hazardous waste. S/S is an established and worldwide accepted disposal technique for hazardous wastes. S/S is an increasingly popular waste management approach in the disposal of combined organic and inorganic industrial wastes. The S/S processes are often combined to alter the waste’s physical and chemical composition. This process allows the pollutants in the waste to stay in the solidified matrix even though the matrix itself may inevitably degrade. The S/S processes can be driven by physical and chemical means, encapsulation, fixation, or adsorption with wastes components (Chen et al. 2019). Solidification is that portion S/S in which materials are applied to the waste to form a solid matrix. The solidification of waste with cement and solidified waste has become a popular way of minimising the atmosphere’s emissions and recycling the waste in manufacturing construction products. Solidification was a mechanism that immobilised CWA’s heavy metals by cement-based solidification (Ababneh et al. 2020; Agamuthu and Chitra 2009; Akyildiz et al. 2017; Anastasiadou et al. 2012; Kaur et al. 2019; Rozumová et al. 2015). S/S of ash from CWIFA has shown that this approach is a good treatment option (Agamuthu and Chitra 2009; Liu et al. 2018). The decrease in heavy metals’ leaching capacity was observed due to the stabilisation period (Anastasiadou et al. 2012).

The solidification process shows that the waste compounds are caught in the porous gel structure’s pores, and heavy metal fastening creates insoluble metal hydroxides. The binders or cement increase the resistance and the compressibility and permeability of the waste. Stabilisation is the other S/S component that uses a physiochemical process to turn contaminants into less mobile and less reactive forms to create a chemically stable condition. For stabilisation, the solubility and toxicity of pollutants were reduced (Qian et al. 2008). The cement volume contributed to lower durability and decreased the resultant leachate concentrations of heavy metals present in CWIFA. By utilising cement as a binding agent, heavy metal stabilisation may accomplish up to some stage. However, detoxification of dioxins cannot be realised (Liu et al. 2018). The probability of S/S of CWIFA is to eliminate and reduce toxic elements under acceptable limits such that the same can be used in manufacturing. The ash of the solidified matrix showed sufficient compressive strength. It is the most widely accepted S/S method before landfill disposal in most countries because it is relatively easy to implement and is low cost.

Cement is the standard binder used on the S/S system. Cement solidification is ideal for inorganic waste, especially
Cement mix indicates the potential to decrease heavy metal concentrations within the permissible limit suggested by the USEPA regulatory (Ababneh et al. 2020; Kaur et al. 2019). The Portland cement was applied to solidify CWIFA and improve the stability of the mixture (Agamuthu and Chitra 2009; Sobiecka et al. 2014). The cement as a binder used for S/S not only solidified the hazardous waste by chemical means but also immobilised the selected toxic elements (Ali Jawaid and Kaushik 2012). Cement-based solidification diminished the metals of the solidified matrices of the leachate. S/S of CWIFA by the cement-based system's method shows that the characteristics of high chlorides and carbon contents tend to weaken the effect of cement solidification, and metal forming hydroxides are less soluble compared to other ionic metal species (Sobiecka et al. 2014). The cement solidification and the leaching rate keep stable and lower than the raw waste ash (Bie et al. 2016).

Studies showed an improvement in heavy metal stabilisation of CWIFA achieved by the S/S of a cement-based system. The increase in the cement/waste ash and curing time enhanced the heavy metal stabilisation rate, and the concentration of metal extract leachability was below detection (Agamuthu and Chitra 2009; Anastasiadou et al. 2012; Bie et al. 2016; Genazzini et al. 2003; Tang et al. 2016). The heavy metals present in the leachate of CWIFA and the alkali-activated matrices' tendency to immobilise heavy metals after their inclusion during the mixing process minimised by geo-polymerisation at a high percentage, and the inclusion of calcium carbonate did not influence the leachability of heavy metals (Tzanakos et al. 2014). All metals, except Fe and manganese (Mn), were inhibited by the solidification of CWIFA using OPC together, and the inclusion of AC steadily decreased heavy metal leaching, especially Zn and AC, encouraging the chemical components and heavy metals extracted into the solidified matrix. (Agamuthu and Chitra 2009). The process of melting had found to preserve the heavy metals in the waste and to offer an efficient way of ultimate disposal (Azni et al. 2005). The solidified process formed on the immobilisation of CWIFA and selected heavy metals was the influence of the raw materials' chemical composition on the stability of the finished product (Sobiecka et al. 2014).

The existence of ettringite causes the decrease of certain leachate substances because of the formation of more stable forms insoluble in water (Rozumová et al. 2015). Portlan-
shows that the TCLP leaching of heavy metals of the blended cement with including washed MWFA is far lower than that of the corresponding regulation and the MWFA mortar fulfilled the legislative constraints for pollution, leaching the contamination with hazardous matter eliminated (Lee 2009; Yang et al. 2018). Based on Table 7 shows the heavy metal of the cement-based system containing CWIFA. Most leaching tests by previous research studies were done on Cd, Cr, Cu, Ni, Pb, and Zn. Based on Table 7, the Cd, Pb, and Zn value of CWIFA increases with an increased inclusion percentage of CWIFA. However, Pb and Zn reading also higher value in 0% of CWIFA.

### Table 7 Heavy metal in different types of cement-based systems containing CWIFA

| Author’s (Year) | % of CWIFA in a different type of cement-based | Heavy Metal (TCLP Hazardous waste limit (mg/l)) | Cd (1 mg/l) | Pb (5 mg/l) | Zn (5 mg/l) | Cr (5 mg/l) | Cu | Ni |
|-----------------|-----------------------------------------------|-----------------------------------------------|-------------|-------------|-------------|-------------|----|----|
| (Ababneh et al. 2020) | 20% of CWIFA (mg/l) | 0 | 6.72 | 19.8 | – | – | – |
| | 20% of treated CWIFA (mg/l) | 0 | 2.92 | 6.8 | – | – | – |
| (Tzanakos et al. 2014) | 20% (75% CWIBA + 25% CWIFA) (mg/l) | <DL | – | 1.2630 | 0.0321 | – | <DL |
| | 30% (75% CWIBA + 25% CWIFA) (mg/l) | <DL | – | 1.3569 | 0.0452 | – | <DL |
| | 50% (75% CWIBA + 25% CWIFA) (mg/l) | <DL | – | 1.5248 | 0.0632 | – | <DL |
| | 20% (50% CWIBA + 50% CWIFA) (mg/l) | <DL | – | 1.9856 | 0.0245 | – | <DL |
| | 30% (50% CWIBA + 50% CWIFA) (mg/l) | <DL | – | 2.0145 | 0.0365 | – | <DL |
| | 50% (50% CWIBA + 50% CWIFA) (mg/l) | <DL | – | 2.1452 | 0.0695 | – | <DL |
| (Anastasiadou et al. 2012) | 40% CWIFA (mg/l) | 0.0021 | 0.3368 | 2.3718 | 0.0481 | 0.3012 | 0.0446 |
| | 50% CWIFA (mg/l) | 0.0056 | 0.5244 | 1.7828 | 0.0707 | 0.5507 | 0.0546 |
| | 60% CWIFA (mg/l) | 0.0071 | 0.3861 | 1.52 | 0.0562 | 0.5962 | 0.0469 |
| | 70% CWIFA (mg/l) | 0.0038 | 0.3540 | 2.8 | 0.0419 | 0.4358 | 0.0212 |
| (Ali Jawaid & Kaushik, 2012) | Soil + 20% CWIFA (mg/l) | 0.115 | 0.747 | – | 0.07 | 0.579 | 0.379 |
| | Soil + 20% CWIFA + 20% Cement (mg/l) | 0.060 | 0.105 | – | 0.045 | 0.896 | 0.291 |
| (Genazzini et al. 2005) | Non-spiked CWIFA (mg/l) | 0.04 | 0.9 | 50 | – | 0.1 | – |
| | 50% CWIFA (non-spiked ash) (mg/l) | <0.02 | 0.4 | 9 | 1.1 | 0.7 | – |
| | 50% CWIFA (0.1% Cd, 1% Cr, 1% Pb and 2.8% Zn) (mg/l) | 5.9 | <0.2 | 136 | 20 | 0.9 | – |
| | 50% CWIFA (5% Pb) (mg/l) | 0.06 | 0.6 | 9 | 0.9 | 0.7 | – |
| (Genazzini et al. 2003) | (w/(c + a) = 0.35, 10% CWIFA (mg/l)) | – | – | – | – | – | – |
| | (w/(c + a) = 0.35, 25% CWIFA (mg/l)) | <0.02 | 0.6 | 0.3 | 0.1 | 0.3 | – |
| | (w/(c + a) = 0.35, 50% CWIFA (mg/l)) | 0.04 | 0.7 | 1.3 | 0.1 | 0.7 | – |
| | (w/(c + a) = 0.5, 10% CWIFA (mg/l)) | 0.02 | 0.3 | 0.04 | 0.2 | <0.1 | – |
| | (w/(c + a) = 0.5, 25% CWIFA (mg/l)) | – | – | – | – | – | – |
| | (w/(c + a) = 0.5, 50% CWIFA (mg/l)) | 0.03 | 0.3 | 0.15 | 0.4 | 0.1 | – |

**< DL = below detection limit**

Conclusions

The health facilities of many countries across the world, including Malaysia, are presently stretched to the maximum in the current Covid-19 pandemic. In addition, a significant amount of CW is generated in the present pandemic, which resulted in a considerable rise in the quantity of challenging medical waste. In Malaysia, CW generated by frontlines at the medical facilities increased by 111.94% in 2020 compared to December 2019. As the pandemic worsened, the volume of CW grew to 173.25 tonnes per month during the subsequent 12 months. The MOH generated almost RM 200 million by managing almost 16,000 tonnes of CW in 2009. To improve the CW management practices in Malaysia, including quality of care and services, the ministry has resorted to privatisation of the CW management with an estimated project cost of RM26.36 billion for a period of over ten years of care. CW in Malaysia is classified as scheduled waste under the Quality (Scheduled Waste) Regulations, 2005. All CWs are filtered at the hospitals or clinics, collected, and sent by concession companies' vehicles to be disposed of at twelve incinerators around Malaysia. Hospital or CW disposal is a significant problem in developed nations. The amount of CW generated is expected to increase nationally and globally. The collection of CW and other urban wastes also poses a risk to the health of citizens and makes
the processing and recycling of materials difficult. A proper incineration process is required to reduce any harmful effects on human beings. Two types of CWA produced from the incineration process are CWIBA and CWIFA.

CW from hospitals and other health care and research facilities has a significant negative influence on human health and the environment. On CW issues, there is an immediate need for increased awareness, education, and a proper waste management strategy. Incineration is the best option for lowering the waste volume and producing new waste in CWIFA and CWIBA. This review gives essential information on how to use ashes from CW incinerators properly. The uncontrolled disposal of these ashes causes significant damage because heavy metal toxicity and the presence of dioxins and furans contaminate the soil, as well as surface and subsurface water. To address this issue, various studies have been conducted on the use of CW incineration ash in cement and concrete, with the results demonstrating that CWIFA may be successfully used in cement and concrete systems. Because the ashes have a low chemical reactivity, additional research should be conducted to boost their reactivity by increasing their surface area or utilising chemical activators to induce pozzolanic reactions in cement-concrete systems. CWIFA has shown promise as an agricultural fertiliser (ash contains macro and micronutrients except for carbon and nitrogen) and as a road and asphalt aggregate. As a result, more research is needed to determine additional viable options for disposing of and utilising the ashes created by CW incinerators. The leaching of heavy metal shows that stabilised and immobilised in different types of cement-based systems. Furthermore, heavy metal leachability studies and strategies for managing metal residues in leachate should be thoroughly researched to ensure proper management and utilisation of CWA for health and environmental safety.

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