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The Impact of Wood Waste Ash on Physical Mechanical Properties of Concrete

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Abstract. In this work is analysing the impact of wood waste bottom ash (WWBA) on the physical mechanical properties of Portland cement concrete (PCC). WWBA is a waste generated in power plants during burning forest residues to produce energy and heat. In 2019, about 19,800 tons of WWBA was generated only in Lithuania. Usually, WWBA is disposed of in landfills, only 26% of WWBA is used in the construction or maintenance of local roads, because of that it is useful to know properties of such WWBA and to analyse possibilities of using it in cement concrete. In the chemical composition of such WWBA type was fixed a big amount ~50% of CO₂. It is known, that C retards cement hydration. Due to stabilisation this process, it was used in the same amounts catalyst waste from oil cracking (FCCCw), which could accelerate hydration processes. Oil refineries worldwide generate more than 800,000 tonnes of FCCCw per year, of which around 20% in Europe and it is the big problem to landfill. In the investigation the amount of Portland cement (5-20% by mass) was replaced by mentioned wastes and properties of fresh PCC (density, slump, flow diameter) and physical mechanical properties of hardened PCC (water absorption, capillary water absorption, ultrasound pulse velocity, density, compressive strength after 28 days and 2 years curing, SEM) were established. It was determined, that by increasing amount of waste (till 20%) the workability of concrete decreases, because used wastes had higher water requirement. The best results were obtained, when 5% of cement was replaced by WWBA. Then compressive strength after 28 days curing comparing to control sample decreased 8%, but after 2 years curing it increased 1%, also the capillary water absorption decreased, denser structure was formed. The obtained results of hardened PCC density, ultrasound pulse velocity and water absorption are similar to control samples.

1. Introduction

Wood is used for heating both in individual houses and in cogeneration plants or other combustion plants. With the wider use of biofuel, incineration inevitably generates waste from this process - ash. It is stated [1] that the volume of biomass ash in boilers and cogeneration plants of district heating companies will increase by one fifth in the last five years. In 2019, almost 20 thousand tons of wood burning ash were formed in Lithuania and this amount is still rising. It is also stated that in the next few years this amount will increase to 100 thousand tons per year. Most of this ash is transferred to waste managers.

Biofuel is considered to be a CO₂ neutral fuel because not burning them and leaving them to rot in a forest or landfill would not reduce CO₂ emissions, simply releasing CO₂ and other greenhouse gases -



methane - during decay. As a tree grows, it absorbs the same amount of CO₂ as burning wood waste [2]. Currently, wood ash is designated as non-hazardous waste, therefore it is subject to norms, rules and other legal acts on non-hazardous waste management of the European Union and the Republic of Lithuania.

Research is needed to find the possibilities of replacing cement in concrete or looking for new alternative binders. Cement is one of the most abundantly produced building materials, which requires significant resources and the production of it has a significant impact on the environment. The cement sector is the third-largest industrial energy consumer in the world, responsible for 7% of industrial energy use, and the second industrial CO₂ emitter, with about 7% of global CO₂ emissions. As the global population rises and more people move into cities, global cement production is set to grow by 12 to 23% by 2050 [3]. The most GHG intense part of cement production (~ 60% of total emissions) is limestone calcination to produce clinker [4].

The use of alternative fuels or the optimization of heat transfer in the production of clinker would help to reduce CO₂ emissions as well as energy and raw material consumption. For environmental reasons, priority is given to reducing the consumption of cement when waste is used as a substitute for cement. The activity of cement substitutes is often lower than that of cement alone. This prolongs hardening and reduces early strength, especially when cement is replaced in large quantities [5].

The properties of wood ash can vary depending on some factors such as wood species, composition, burning temperature, humidity, etc. When the combustion system in boilers is operating efficiently, the carbon content may be only 1%, if inefficiently - more than 10% and may exceed 70%. In addition to carbon, forest ash contains Ca, Si, Al, Mg, Na, K and Fe [6].

Wood waste ash has great potential for efficient use as a cement substitute for the production of blended cement systems and for the production of structural concretes and mortars of suitable strength and durability [7]. Chowdhury [8] reviewed the work done on the reuse of wood ash in concrete from 1991 to 2012.

At present, oil-refineries generate more than 800 thousand tons of catalyst waste per year worldwide [9], of which around 20% in Europe [10]. Lithuania produces 200 tons per year. The catalyst waste (FCCCw) constituents are an aluminosilicate faujasite-type zeolite, an essentially amorphous alumina active matrix, clay and a binder. It possesses a high content of Al₂O₃·SiO₂ of c.a 90% (w/w) [11].

Authors report [12] that 9% of catalyst waste (FCCCw) replacement of cement in the mixture accelerates cement hydration and increases the strength of the light composite with glass beads. FCCCw from the Portuguese oil refinery also possess a very high pozzolanic activity. This spent catalyst has already been tested in cement pastes, mortars and concretes for different applications [13, 14].

The aim of the current study is to assess the viability of partially replace the cement with the catalytic cracking catalyst waste (FCCCw) and wood waste bottom ash (WWBA) as well as evaluate their impact on the physical mechanical properties of Portland cement concrete (PCC).

2. Materials and methods

The following raw materials were used to form the concrete samples: cement CEM I 42.5 R (conforms the standard EN 197-1), FCCCw generated by AB Orlen Lietuva oil refinery (Lithuania), WWBA generated in power plants (Lithuania), natural sand, granite crushed stone.

The mineral composition of the cement is: C₃S - 56.6%, C₂S - 16.7%, C₃A - 9.0%, C₄AF - 10.6% and 7.1% others (alkaline sulphates and CaO). Particle density 3.1 g/cm³, bulk density 1.1 g/cm³, compressive strength after 28 days 55 MPa, initial time 180 min. Chemical composition of the cement, FCCCw and WWBA are presented in table 1. The majority of the ash composition consists of Ca compounds, i. e. 22.7%, as well as the organic part (53.7%). More than 10% organic matter in ash indicates that the combustion process is not optimal and needs to be changed or optimized [15].

Sand fraction 0/4 conforming to standard EN 12620 requirements. The data of the study of physical properties of sand are presented in table 2. Two crushed granite aggregates (fraction 5/8, bulk density 1300 kg/m³ and 11/16, bulk density 1410 kg/m³).

Table 1. Chemical composition of the cement, catalyst waste and bottom ash used (% , by mass).

| Compound | Chemical composition (% , by mass) | | |
|------------------------------------|------------------------------------|-------|-------|
| | CEM I 42.5 R | FCCCw | WWBA |
| SiO₂ | 20.4 | 50.1 | 8.34 |
| Al₂O₃ | 4.0 | 39.4 | 1.54 |
| Fe₂O₃ | 3.6 | 1.3 | 0.949 |
| CaO | 63.2 | 0.5 | 22.7 |
| MgO | 2.4 | 0.49 | 2.57 |
| SO₃ | 3.1 | 2.3 | 2.79 |
| K₂O | 0.9 | 0.07 | 3.78 |
| Na₂O | 0.2 | 0.2 | 0.212 |
| Mn₂O₃ | - | 0.03 | - |
| Cl | 0.05 | 0.008 | 0.269 |
| Loss by ignition | 2.15 | 3.5 | - |
| CO₂ | - | - | 53.7 |

Table 2. Physical properties of sand.

| Characteristic | Test results |
|--|--------------|
| Particles density, kg/m³ | 2500 |
| Water absorption, % | 0.570 |
| Bulk density, kg/m³ | 1575 |

FCCCw particles are spherical, particle density 2750 kg/m³. WWBA from a greenhouse crops boiler where the biofuel is burnt is a mixture of oak, coconut fiber, litterfall and deforestation waste. Burning temperature is 1000–1200°C, burning time at this temperature - ~30 min. The boiler house produces approximately 1 ton of ash per day. The physical properties of WWBA fraction 0/1 are given in table 3. The curve of granulometric composition of WWBA is provided in figure 1.

Table 3. WWBA properties.

| Characteristics | Test results |
|---|--------------|
| Bulk density, kg/m³ | 635 |
| Water absorption after 7 days, % | 44.1 |

A new generation of superplasticizer based on polycarboxylic ether polymers is used in all mixtures. Density of 1.04 g/cm³, pH value at 20°C temperature, 20% solution is 6.5. Superplasticizer conforms the requirement of EN 934-2. All samples were prepared with drinking water based on the requirements of European standard EN 1008.

Five concrete mixtures with a designation codes C0, C5B5, C10B10, C0B5 and C0B10 was mixed. Concretes mixtures were formulated by partially replacing the cement with FCCCw and WWBA within the range 5 to 10%, by mass. Table 4 presents the concrete mixtures compositions and the notation adopted for each mixture. Superplasticizer corresponds to 0.6% of the binder content.

Cube-shaped samples (100×100×100 mm) formed from the prepared mixtures were kept under normal conditions in the moulds for 1 day, followed by 27 days in water at 20°C ± 2°C. Production and hardening of concrete samples for compressive strength determination were conducted according to EN 12390-2. The compressive strength of concrete specimens based on EN 12390-3, the density was determined according to EN 12390-7. The density of the mixtures was determined according to EN 12350-6, the slump - according to EN 12350-2, the flow - according to EN 12350-5. Water absorption of samples were established according to the methodology described in the literature [16].

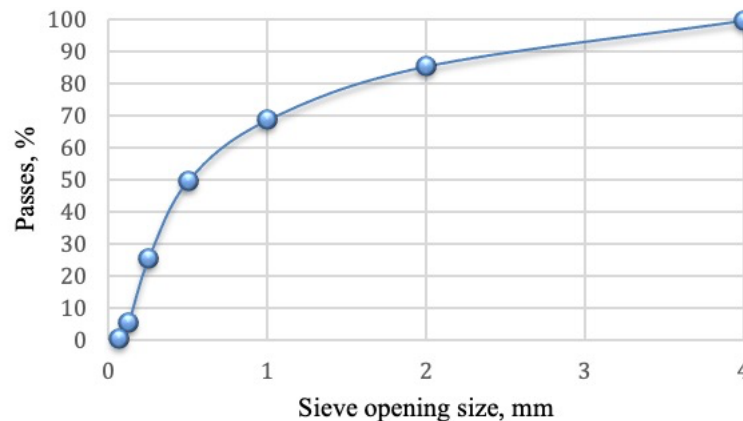


Figure 1. WWBA granulometric composition

Table 4. Compositions of concrete mixtures (kg/m³) and corresponding notation.

| Notation | Binder (Cement+FCCCw+WWBA) | | | Sand | Granite crushed stone 5/16 | Water | Plasticizer | W/B |
|---------------|-------------------------------|-------|------|------|-------------------------------------|-------|-------------|------|
| | Cement | FCCCw | WWBA | | | | | |
| C0 | 300 | 0 | 0 | 980 | 1000 | 165 | 1.8 | 0.55 |
| C5B5 | 270 | 5 | 5 | 980 | 1000 | 165 | 1.8 | 0.55 |
| C10B10 | 240 | 10 | 10 | 980 | 1000 | 165 | 1.8 | 0.55 |
| C0B5 | 285 | 0 | 5 | 980 | 1000 | 165 | 1.8 | 0.55 |
| C0B10 | 270 | 0 | 10 | 980 | 1000 | 165 | 1.8 | 0.55 |

Note: 50% - 5/8 fraction and 50% - 11/16 fraction of granite crushed stone

Fracture surfaces of hardened concretes were analyzed by scanning electron microscopy (SEM) using secondary electron (SE) mode using a TESCAN VEGA3 SEM microscope (Czech Republic). Prior to the test, the specimen surface was covered with a thin golden layer by gold electron vacuum evaporation.

Ultrasound propagation time was measured using the equipment “Pundit 7” with two 54 kHz transducers. The ultrasonic pulse velocity (UPV) was computed using equation (1):

$$UPV = \frac{l}{\tau} \text{ (m/s)} \quad (1)$$

where: l - the ultrasonic pulse path length through the sample i.e., the distance between the two transducers that in this case is the length of the specimen, m (0.10 m for concrete specimens) and τ - signal propagation time provided by the test equipment, s.

3. Results and discussions

The determined concrete slump is presented in figure 2, concrete flow in figure 3. The results of slump and flow show that FCCCw and WWBA change the consistency of the concrete mixture thus reducing the slump and flow of the concrete mixtures. When the amount of FCCCw and WWBA waste in the concrete mixture reaches 10%, the workability of the mixture deteriorates, the slump and flow are significantly reduced. This might have been due to the high organic content in the wood waste ash. Scientists [17] believe that wood biomass ash is a hydrophilic material which particles tend to swell when absorbing water into the pores. Irregularly shaped and porous ash particles tend to not only absorb water but also reduce the workability of the mortar [18]. Similar results were obtained by other researchers [19] who observed that the replacement of cement with wood ash has a negative effect on the workability of freshly produced concrete.

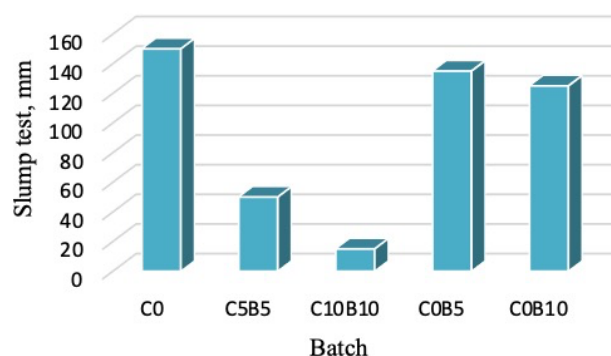


Figure 2. The dependence of concrete slump on the amount of waste

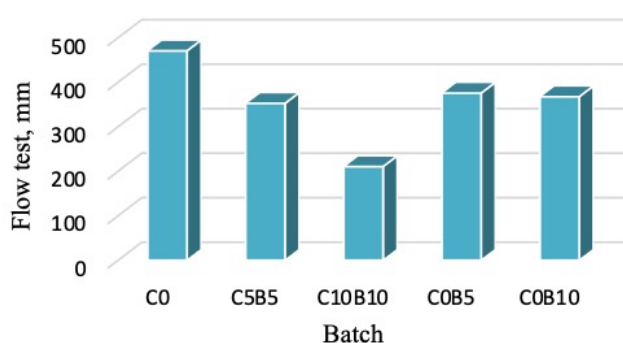


Figure 3. The dependence of concrete flow on the amount of waste

The results presented in table 5 show that the density of concrete mixtures in all batches remains similar, ranging from 2380 to 2440 kg/m³. The average densities and compressive strengths of concrete samples made of mixtures designated as C0, C5B5, C10B10, C0B5 and C0B10 after 28 days and 2 years of hardening are shown in figures 4 and 5.

Table 5. Density of concrete mixtures.

| Mark | Mix density, kg/m ³ |
|---------------|--------------------------------|
| C0 | 2440 |
| C5B5 | 2403 |
| C10B10 | 2398 |
| C0B5 | 2398 |
| C0B10 | 2380 |

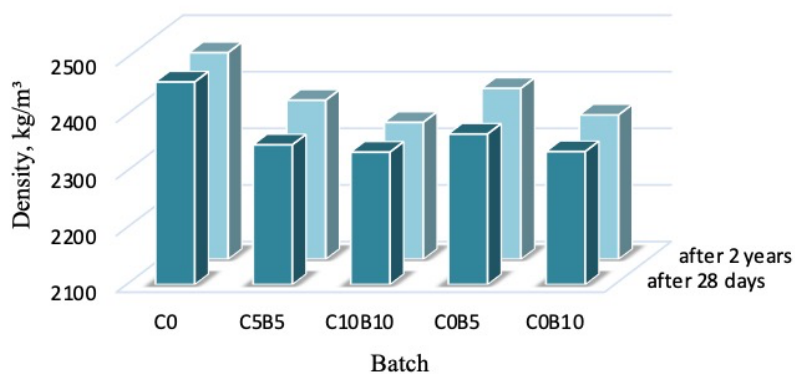


Figure 4. Density of concrete with 0, 5 and 10% (w/w) of cement replacement with FCCCw catalyst and WWBA ash after 28 and 2 years curing

The obtained results in figure 4 show that mixing concrete with different amounts of FCCCw and WWBA determines the density which varies from 2334 to 2366 kg/m³ after 28 days, from 2342 to 2402 kg/m³ after 2 years. The highest density values are for concrete samples made of a mixture marked C0B5 and the lowest for C10B10. The density of the samples after 28 days and 2 years with the maximum amount of waste decreased by 5.0% compared to the control samples.

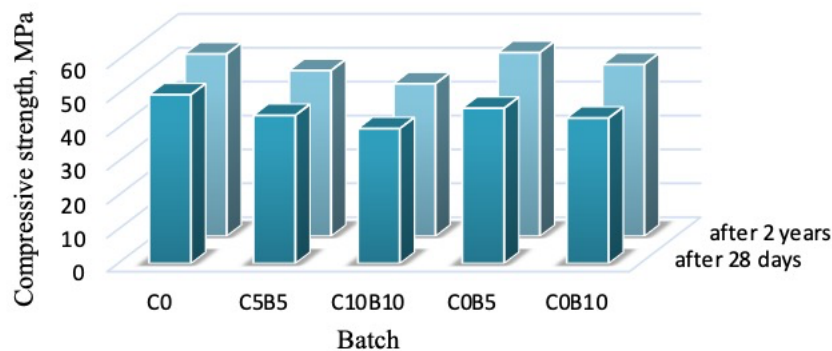


Figure 5. Compressive strength of concrete with 0, 5 and 10% (w/w) of cement replacement with FCCCw catalyst and WWBA ash after 28 and 2 years of age

The results presented in figure 5 show that as the amount of FCCCw and WWBA waste increases, the strength of the concrete samples decreases. The average compressive strength of the samples made from the control mixture after 28 days is 49.8 MPa, after 2 years - 53.8 MPa. When the forming mixture contains 10% FCCCw and WWBA, the compressive strength decreases by 20.1% after 28 days and by 16.4% after 2 years compared to the control samples. The best results are obtained by adding 5% WWBA to the mixture, the compressive strength of concrete decreases by 8.0% after 28 days, but after 2 years it increases by approximately 1%.

As expected, the results in figure 6 of ultrasonic pulse velocity in concretes presents the same trend as for compressive strength and density results (figure 4 and 5, respectively). Namely, the highest UPV was recorded in concrete samples C0B5.

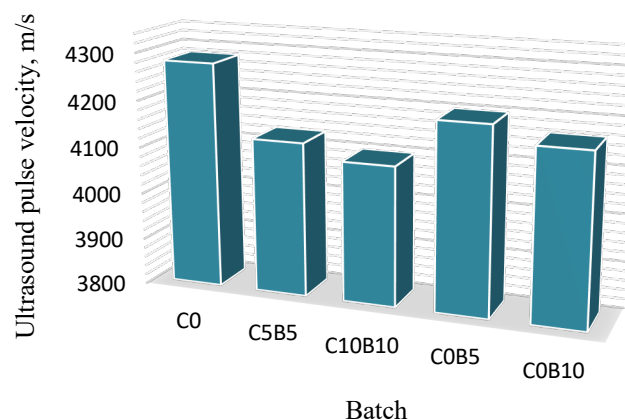


Figure 6. The results of concrete ultrasound pulse velocity after 28 days curing

Water absorption results of concrete are presented in figure 7. It is observed that with the increase of wood ash and catalyst waste up to 10%, water absorption also increases. The water absorption of the samples with 5% WWBA remains similar compared to that of the control samples and after 24 hours of soaking, it is 3.8%. It is observed that after 1440 min the water absorption increases sharply, and later the concrete practically no longer absorbs water.

Figure 8 present the results of capillary rate of mass flow. It is seen, that capillary rate of mass flow of samples C0B5 and C0B10 are less by approximately 25%. This shows that WWBA can reduce the open porosity of concrete and not impair the resistance of concrete to freeze-thaw cycles.

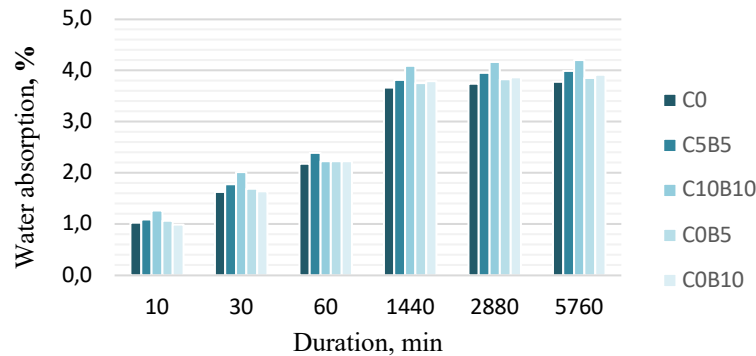


Figure 7. The dependence of water absorption on the amount of waste

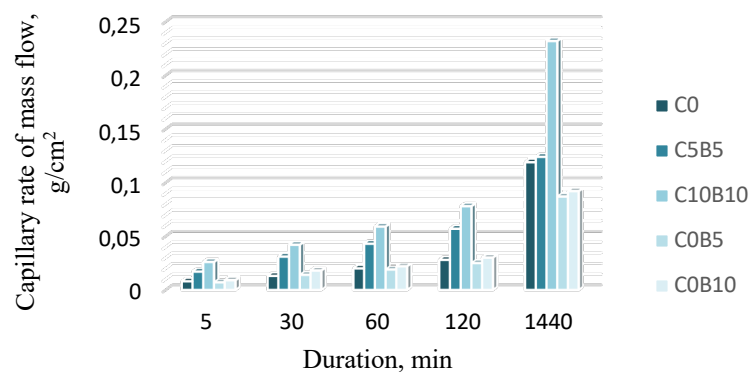


Figure 8. The dependence of concrete capillary rate on the amount of waste

Figure 9 shows the microstructure of samples with 5% WWBA after 28 days of hydration. The images reveal conventional cement hydration products: the dendritic crystal typical of crystallization morphology of portlandite (CH), the acicular crystals of calcium sulfoaluminates hydrated phases, such as ettringite (E) dispersed in a fibrous matrix of calcium silicates hydrates (C-S-H).

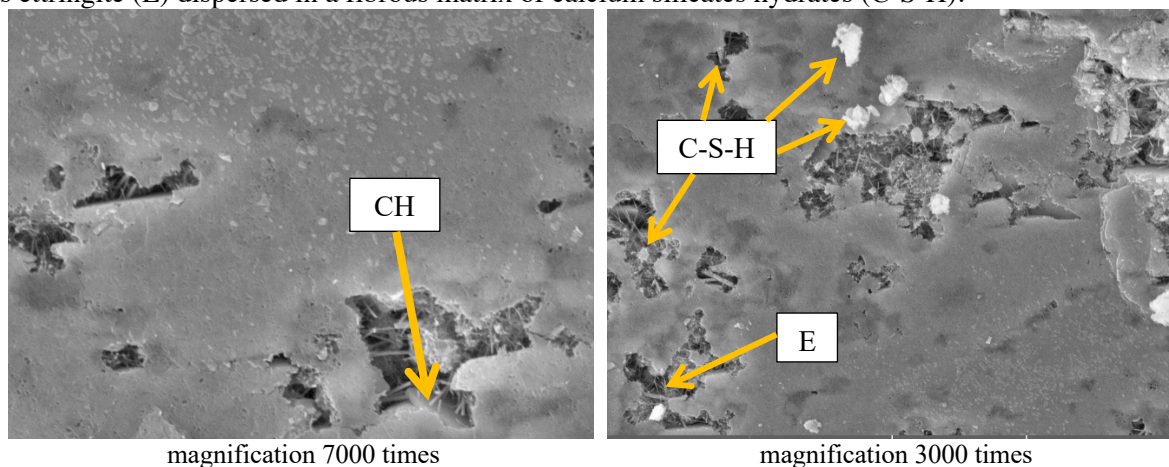


Figure 9. Images of the microstructure of concretes with 5% of WWBA incorporation obtained on a fractured surface (Note: CH-portlandite; E-ettringite; C-S-H - calcium silicate hydrate)

4. Conclusions

The performed research confirmed the results obtained in the world practice, revealing the possibilities of using the ash from the incineration of wood waste for concrete mixtures.

The research reveals positive prospects for the use of wood ash for concrete mixtures. By replacing 5% of the cement mass with wood ash, the compressive strength of concrete decreases by 8% after 28 days and increases by about 1% after 2 years compared to control concrete samples.

The density, UPV, water absorption of these samples are quite similar to control samples. Positive results were obtained for the capillary rate of mass flow, which showed that the capillary rate of mass flow for samples with 5% and 10% WWBA decreases by approximately 25%. This could be an indicator of the greater resistance of such concrete to freeze-thaw cycles, but further research is needed.

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